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A FUNCTIONAL DESCRIPTION OF A DIGITAL FLIGHT TEST SYSTEM FOR NAVIGATION AND GUIDANCE RESEARCH IN THE TERMINAL AREA

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16. Abstract

A guidance, navigation, and control system, the Simulated Shuttle Flight Test System (SS-FTS), was installed in the NASA-ARC CV-990 aircraft and successfully flight tested in 1972. When interfaced with existing aircraft systems, the SS-FTS provides a research facility for studying concepts for landing the space shuttle orbiter and conventional jet aircraft.

The SS-FTS, which includes a general-purpose computer, performs all computations for precisely following a prescribed approach trajectory while properly managing the vehicle energy to allow safe arrival at the runway and landing within prescribed dispersions. The system contains hardware and software provisions for navigation with several combinations of possible navigation aids that have been suggested for the shuttle. The SS-FTS can be reconfigured to study different guidance and navigation concepts by changing only the computer software, and adapted to receive different radio navigation information through minimum hardware changes. All control laws, logic, and mode interlocks reside solely in the computer software.

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SUMMARY

A guidance, navigation, and control system, the Simulated Shuttle Flight Test System (SS-FTS), was installed in the NASA-ARC CV-990 aircraft and successfully flight tested in 1972. When interfaced with existing aircraft systems, the SS-FTS provides a research facility for studying concepts for landing the space shuttle orbiter and conventional jet aircraft.

The SS-FTS, which includes a general-purpose computer, performs all computations for precisely following a prescribed approach trajectory while properly managing the vehicle energy to allow safe arrival at the runway and landing within prescribed dispersions. The system contains hardware and software provisions for navigation with several combinations of possible navigation aids that have been suggested for the shuttle. The SS-FTS can be reconfigured to study different guidance and navigation concepts by changing only the computer software, and adapted to receive different radio navigation information through minimum hardware changes. All control laws, logic, and mode interlocks reside solely in the computer software.

INTRODUCTION

NASA-Ames Research Center recognized the need for early flight tests of various system concepts to ensure continued orderly development of the shuttle G&N system. After a year and a half of in-house and contractor effort (refs. 1-6), preliminary navigation, guidance, and control concepts had been developed for what appeared to be a critical phase of the shuttle mission, the end of the reentry to landing. A contract was awarded to Sperry Flight Systems in mid-1971 to design and fabricate a suitable avionics system for flight testing these concepts. This avionics system, the Simulated Shuttle Flight Test System (SS-FTS), was delivered in May 1972, installed in the CV-990 Galileo I, and flight tested for the first time on June 5, 1972. A total of 58 hr of flight testing was conducted during the last half of 1972. Flight test procedures and results are described in references 7-9.

The SS-FTS was developed as a research facility for studying navigation, guidance, and control concepts for the terminal area and landing approach of a space shuttle vehicle. The system performs all computation for precisely following a prescribed approach trajectory while properly managing the vehicle energy to allow safe arrival at the runway and landing within prescribed dispersions (ref. 10). The system contains hardware and software provisions for navigation with several combinations of possible navigation aids that have been suggested for the shuttle. The system architecture was chosen so it can be reconfigured to study different guidance and navigation concepts by changing only the computer software and adapted to receive different radio navigation information through minimum hardware changes.

All control laws, logic, and mode interlocks reside solely in the computer software, and changes to any of these can be made rapidly and easily.

The digital avionics system, with some components reconfigured, is presently being installed in a second NASA/ARC CV-990 Galileo II. The CV-990 Galileo I, in which the system was initially installed and the space shuttle landing concepts flight tested, was destroyed as a result of a midair collision. NASA purchased the replacement aircraft, Galileo II, to continue its airborne research activities.

The primary objective of this report is to provide potential experimenters with an understanding of the functional capabilities of the avionics system to enable them to determine if this versatile research facility can be used in their programs. This objective could be met by a discussion of the avionics system as installed in either aircraft.

The secondary purpose of the report is to provide a general reference on the results of the flight test of the space shuttle landing concepts. This document therefore describes the SS-FTS as installed in the NASA CV-990 Galileo I, with which the flight tests were made.

SYMBOLS

ac	alternating current
ACPRS	Ames/Cubic precision ranging system
A/D	analog to digital
ADDAS	Airborne Digital Data Acquisition System
AFB	Air Force base
AGL	above ground level
ALT	altitude
A/P	automatic pilot
APD	approach progress display
ARC	Ames Research Center
ARINC	Aeronautical Radio Inc.
ATC	air traffic control
ATR	air transport rated
BCD	binary coded decimal
AUTO	automatic
BITE	built-in test equipment
CADC	central air data computer
CSE	course
cm	centimeter
D/A	digital to analog
dc	direct current
D/D	digital to digital
deg	degree
DEP	data entry panel

DH	decision height
DME	distance measuring equipment
EIU	electronic interface unit
ft	feet
g	gravitational unit
gm	gram
G&N	guidance and navigation
GS	ILS glide slope
hr	hour
I/O	input/output
ILS	instrument landing system
INS	inertial navigation system
kHz	kilohertz
km	kilometer
lb	pound
LOC	ILS localizer
LRU	line replaceable unit
m	meter
mi	mile
msec	millisecond
MSP	mode select panel
mV	millivolts
N	newton
NASA	National Aeronautics and Space Administration
navaid	navigational aids
nm	nautical mile
RAD	radar altimeter

R/D	raw data
REV	reverse
RNAV	area navigation
SBLGS	scanning-beam landing guidance system
SC	Special Committee
sec	second (time)
SEL	select
SS-FTS	Simulated Shuttle Flight Test System
SSV	space shuttle vehicle
SSV-SIM	space shuttle vehicle simulation
V	volt
VOR	very high frequency omnirange
μsec	microsecond (time)
[LABEL]	The label within the brackets indicate the name of a system switch or the position of the switch.

CV-990 AIRCRAFT

Configuration

The NASA Convair 990 aircraft (fig. 1) is a swept-wing-and-tail four-engine transport similar in appearance and performance to most other present-day jet transports. An unusual feature is the four wing-mounted anti-shock pods, which reduce drag at high speeds and also serve as fuel tanks. The aircraft is of all-metal construction with full cantilever wing and tail surfaces. It is powered by four General Electric CJ-805-23B axial flow aft-fan turbojet engines delivering a maximum thrust of 71,400 N (16,050 lb) each. A three-view drawing of the aircraft is shown in figure 2, and the pertinent physical characteristics are listed in table 1.

Aerodynamic Controls

The airplane is equipped with conventional ailerons and spoilers for lateral control and a rudder for directional control. Longitudinal trim is provided by an all-movable horizontal stabilizer, and longitudinal control by tab-controlled elevators. The stabilizer is hydraulically actuated with electrical and mechanical backup systems. The elevators are controlled through the servo action of tabs on the trailing edge. The tabs are mechanically controlled by cockpit column position. The wings are equipped with full-span Krueger flaps on the leading edge and partial-span, double-slotted Fowler flaps on the trailing edge.

Space Shuttle Simulation

The capability of the CV-990 aircraft to provide a valid simulation of the space shuttle vehicle is discussed in reference 8.

AVIONICS SYSTEM

General Description

The Simulated Shuttle Flight Test System (SS-FTS) is an integrated digital avionics system built by Sperry Flight System Division for installation in the NASA/ARC CV-990 aircraft. The intent was to provide a research facility that could be used to study space shuttle vehicle approach and landing concepts as well as problems associated with the terminal area, approach, and landing of conventional jet transports (for example, RNAV, ATC, noise abatement, etc.).

The avionics system provides two operating configurations: (1) a digital autopilot for a conventional jet transport (CV-990); and (2) a space shuttle simulator (SSV-SIM). Each configuration has several modes of operation, which are explained later. In both major configurations (SSV and CV-990), the pilot can select completely automatic control, a manual flight director mode using a side-stick controller, or a manual flight director mode using the control yoke of the aircraft. The sidearm controller provides rate commands to the attitude stabilization loop.

The digital autopilot replaces the normal CV-990 analog SP-30 autopilot, providing all the conventional SP-30 autopilot functions, and vertical speed hold, INS nav, and an autoland capability. As a flight facility to study space shuttle vehicle approach and landing, the system performs all

terminal area navigation, guidance, and control functions from high altitude to touchdown. The pilot can reconfigure the system from the conventional jet transport autopilot mode to the space shuttle flight test system by operating the appropriate switches; no equipment need be changed.

System Architecture

The avionics system is designed around a Sperry 1819A general-purpose digital computer, which was originally developed for use in the Boeing supersonic transport. A data adapter provides the interface between the digital computer and all other system components and sensors. The digital computer provides increased computational capability, ease of programming, and flexibility to the system.

Figure 3 shows the transition from the conventional SP-30 autopilot system to the SS-FTS. Figure 3(a) presents the conventional SP-30 autopilot system. The controller houses all the SP-30 engage and mode controls. The blocks labeled "navigation equipment" and "fore and aft accelerometers" represent the autopilot sensing elements. The flight control computer performs the necessary shaping of all stabilization and command signals coming from the sensing elements. The outputs of the flight computer are commands into the stabilization computer, which amplifies the signals to drive the elevator, rudder, and aileron servos in response to errors or commands. The stabilization computer also monitors the operation of the autopilot to determine whether the system is functioning properly, and it supplies signals for the actuation of the stabilizer trim system. The trim servo positions the horizontal stabilizer in response to commands from the

autopilot for pitch trim. Interlocks prevent system engagement when the system is not operating properly.

The configuration shown in figure 3(b) results from removing three units from the conventional SP-30 autopilot: the controller, the flight control computer, and the stabilization computer. The remaining components are common to both the SP-30 and the SS-FTS systems. Figure 3(c) shows how the SS-FTS digital avionics system components are integrated with the remaining aircraft SP-30 components through the connectors (J1000, J1001, J1500, J1501, and J1800) exposed by the removal of the three components. The SS-FTS controller houses all the SS-FTS engage and mode controls. The data adapter, the 1819A digital computer, and the power control unit replace the flight control computer and the stabilization components.

Figure 4 is a simplified system block diagram, which indicates the central role of the data adapter. The data adapter provides the required interface between the 1819A digital computer and other airborne equipment onboard the CV-990 aircraft. The data adapter controls all information transfer (between the various subsystems, sensors, displays, and the digital computer) along with the necessary signal conditioning including A/D, D/A, and D/D conversions. In the power control unit, the data adapter interfaces with the CV-990 electromechanical servos that drive the CV-990 aerodynamic control surfaces in response to commands from the digital computer. For manual operation, the data adapter processes side-stick commands in response to pilot inputs and drives the control surfaces via the power control unit. For automatic control, the control surface commands are generated by the system and the pilot acts as a systems monitor.

For both the automatic and manually flown trajectories, the pilot is informed of approach progress by way of control panels and a display as described below.

Communications between the pilot and the system are provided by three control panels and an approach progress display. The mode select panel provides for selection and annunciation of the various system modes. The data entry panel and the status display provide the pilot with the capability to input data to the computer. The status panel also provides an alphanumeric readout for display of inputs to and outputs from the computer. The status panel includes four pushbutton switches for conducting preflight tests and annunciating inflight failures. The approach progress display annunciates to the pilot the principal phases or modes of system operation from initiation of the approach through touchdown on the runway as the aircraft flies the simulated SSV trajectory.

System Features

The primary features of the SS-FTS are shown in table 2. The system provides a hierarchy of operating modes from manual control with the pilot using raw-data displays, to fully automatic flight including automatic landings. Use of a general-purpose digital computer allows a wide latitude for experimentation with various guidance laws, equation formulations, flight profiles, and other programmed control elements. All control laws, logic, and mode interlocks reside solely in the computer software; the modular software package allows any one portion of the program to be modified with a minimum effect on the others.

The system was designed to investigate the different navigational aids being considered for the SSV approach and landing. Candidate systems

include conventional radio navigation aids (navaids), microwave scanning beam ILS, precision radar, and multilateration beacon transponders. Early NASA flight studies have concentrated on the use of conventional radio navigational aids (i.e., VOR, DME, ILS) that are well understood and widely available. The specific navigation and guidance concepts are discussed later in this report.

The system uses a filter to obtain inertial smoothing of the navaid data. The filter combines the navaid and inertial data to take advantage of the short-period inertial accuracy and the long-period navaid accuracy. The filter also minimizes the effect of data dropout from one or more of the navigation data sources during a flight.

Specified parameters in the software program can be changed in flight, but only within predefined and safe limits. This technique guards against accidentally inserting unsafe parameter values or changing the wrong value in the computer. This access allows rapid evaluation of a series of gain and filter parameters during a single flight.

The pilot's displays are under computer control, thus allowing messages and display sensitivities to be modified by computer program changes. The function of a switch, which is under computer control, can be changed by relabeling the switch and changing the computer program.

System Testing

Ground-based facility. - A software/hardware ground-based Validation Facility was developed to validate the computer software and accomplish system checkout, as well as to obtain preliminary information on system performance prior to a flight test. With this facility, a system concept can be simulated and validated for software correctness and performance prior to actual flight testing.

The Validation Facility contains a complete six-degrees-of-freedom simulation of the CV-990 vehicle, using components (i.e., computer, data adapter) that are identical to the SS-FTS airborne avionics hardware. Figure 5(a) shows the Validation Facility equipment rack with the duplicate airborne hardware components, and the various computers, recorders and simulation equipment which make up the facility. The ground-based cockpit associated with this facility is used for pilot training and familiarization (fig. 5(b).

<u>Preflight testing</u>. - Most preflight testing is done automatically by the onboard computer, although certain test functions require pilot action. The preflight test program, which is initiated by the selection of appropriate switches, offers the pilot a means of testing the SS-FTS prior to takeoff. This test checks system nulls, discretes, all panel operations, computer BITE, data adapter end-arounds, sensor responses, servo step responses, up and down trim rates, HZ6F display, and all aspects of safely disengaging the autopilot in case of detected inflight faults. If a malfunction occurs, a failure indication will appear and a diagnostic message will provide information to help pinpoint the problem source. The entire system is thus tested prior to flight without the requirement for a check list. A successful preflight test can be completed in a little over one minute.

<u>Inflight monitoring</u>. - A self-test program performs inflight monitoring of all discretes, valids, and servos positions providing rapid determination of go/no go conditions. This program performs a functional evaluation of the computer operation without interferring with the operation of the main program. The program alerts the pilot to failures in any of the sensors, control or display components.

Cockpit Displays and Controls

Figure 6 shows the flight deck layout. The test pilot operates the SS-FTS from the right-hand seat in the CV-990 aircraft. The right-hand side of the instrument panel has been modified to accept the system's special displays and panels. In addition, a side-stick hand controller (fig. 4) was installed for manual operation in a flight director mode.

Flight Director

The HZ6F horizon flight director provides the usual cross-pointer flight director display (fig. 7). In addition, a master system warning light on the upper left of this instrument indicates that the pilot should check the status panel for a message. The message may be a notice of a system or sensor failure, or a notice to the pilot for some action such as a change in radio frequency.

Status Panel

The status panel (fig. 8) includes includes a 12-character alphanumeric display and four switches. The status panel is used to initiate preflight ground tests and to display maintenance monitor and inflight failure diagnostic messages. The panel is also used to display information entered into the computer through the data entry panel (DEP) described later. The alphanumeric readout and the switch indicator outputs are all hard-wired discretes to the data adapter.

Some of the various messages that can be displayed to the test pilot during the SSV and CV-990 mode operation of the system are shown below:

Message	Remark
ON G/S BEAM	SSV pitch mode annunciation
TUNE TO DME	Tune DME command
ALT. FAIL	Barometric altimeter data not valid
SPD BRK = 45	Speed brake setting command

As noted previously, pilot attention is called to important messages by the master alert light on the flight director. These include all failure messages, commands requiring pilot action, changes in navigation sensors used, and all raw-data mode annunciation.

The four switches on the status panel are used only on the ground during the preflight tests. The ground-based functions of these four switches are explained below:

1. [CV-990 TEST]. When depressed, this switch is illuminated and the CV-990 portion (i.e.. digital autopilot) of the ground-based preflight test begins. The majority of the preflight testing is done completely automatically by the onboard digital computer, but certain tests require pilot action. The alphanumeric display instructs the pilot of any necessary action he must take to complete the test. Upon successful completion of the CV-990 portion of the preflight test, a "TEST OK" message is displayed. A successful preflight test can be completed in a little over one minute.
2. [SSV TEST]. When depressed, this switch is illuminated and the SSV portion of the preflight test beings. The SSV preflight test is

similar to the CV-990 preflight test, but different hardware and software features of the system are checked.

3. [VERIFY]. The [VERIFY] button is used during some portions of the preflight test when the pilot must verify that some appropriate action has taken place. The verification request is designated on the alphanumeric display as a "V" in the right section of the display. The pilot is to push the [VERIFY] button on the status panel for each such message containing a "V", provided the appropriate action has taken place. For example, at one point in the test, the pilot is instructed to verify that all alphanumeric segments are lighted. If all segments are lighted, he presses, the [VERIFY] switch; if one segment is burned out, however, he presses the [FAIL] switch on the status panel.

4. [FAIL]. This switch is pressed during the preflight test when the pilot is asked to verify an action which has not taken place as in the example above. Once the [FAIL] button is pressed, it is lighted, and the name of the faulted line replaceable unit (LRU) is displayed on the alphanumerics. Pressing the illuminated [FAIL] button then causes the test diagnostic number to be displayed. The test diagnostic number provides information for maintenance purposes.

As the test progresses, the pilot will be requested (via the alphanumeric display) to perform several operations such as: engage A/P, push stick, press disconnect button, etc. If an operation is performed and the results are unsuccessful, the instruction will remain until the [FAIL] button is

pressed. A successful result allows the system to proceed to the next step in the preflight test.

If a portion of the preflight test performed automatically by the digital computer fails, the [FAIL] light will be illuminated and the name of the failed LRU displayed. If the system inflight monitoring routine detects an inflight failure, the [FAIL] switch is illuminated. In addition, the alphanumeric display will indicate the name of the failed LRU.

Data Entry Panel

The data entry panel (DEP) is used in conjunction with the status panel to provide for pilot communication with the airborne computer. The DEP is mounted in the center console just below the status panel. It provides the pilot with the capability to establish or modify certain system parameters during flight and to command stored data to be alphanumerically displayed on the status panel. The DEP, in conjunction with the status panel, is also used during preflight checkout to determine system flight readiness status.

The DEP (fig. 9) consists of a 5x6 matrix of lighted alphanumeric keyborad switches, a [LETTER/NUMBER] selector switch, a [CLEAR] switch, and an [ENTER] switch. As the alphanumeric keys are pushed the corresponding letter/number appears on the status panel 12-character display. The use of the alphanumeric keys is obvious; the functions of the remaining keys [DELETE], [(blank)], [*], [-], [LETTER/NUMBER], [CLEAR], and [ENTER] are explained below:

1. When the pilot presses the [DELETE] key, the last character displayed on the status panel is erased or deleted. If

the pilot presses the key twice in sequence, the last two characters on the display are erased. The next character the pilot presses will appear in the place of the last deleted character.

2. The [(blank)] key inserts a blank or a space into the status panel display.
3. The [*] key is used as a decimal point.
4. The [-] key is the standard negative sign.
5. The [LETTER/NUMBER] key which has two independently illuminated segments, is used to select whether letters or numbers are entered from the top two rows of the DEP keyboard. When letters are selected, the [LETTER] portion of the key is illuminated. At this time, all of the 5x6 matrix of keys are backlighted and used to input letters to the status panel. If numbers are selected, the [NUMBER] portion of the [LETTER/NUMBER] key is illuminated. Then only the top two rows of alphanumeric keys are illuminated, and they are used to input numbers into the status panel. At this time, although not illuminated, the remaining portion of the alphabet, K-Z, may be used. The special keys in the matrix ([DELETE], [(blank)], [*], [-]) are always backlighted and are not affected by the position of the [LETTER/NUMBER] key. The selected state (illuminated portion) of the [LETTER/NUMBER] key alternates each time the key is pushed.
6. The [CLEAR] key is backlighted at all times and is used to clear the status panel of any previously entered data. Whereas the

[DELETE] key clears only the last character entered into the status panel, the [CLEAR] key erases all the characters on the status panel.

7. The [ENTER] key is backlighted at all times. After the pilot has used the DEP to enter data into the status panel and verified that the data are correct as displayed, he may enter the data into the system by pushing the [ENTER] key. Once the data have been entered into the system, the status panel is cleared automatically.

Mode Select Panel

The mode select panel (MSP) provides for pilot selection of the various modes for each of the two operational configurations of the SS-FTS. The two system operating configurations are selected by the [CV-990/SSV-SIM] selector switch near the center of the panel (fig. 10). The [CV-990] configuration consists of the normal autopilot and flight director modes utilizing the digital flight control system. The [SSV-SIM] configuration provides for automatic pilot and flight director functions for the simulated shuttle vehicle energy management and landing.

The 16 MSP switches can be divided into three functional groups. The first group used in both configurations includes the three centrally located toggle switches and the three square pushbutton switches on the upper right side of the panel. The second group comprises the seven pushbutton switches located to the left of the central toggle switches and operational only when the system is in the CV-990 configuration. The third group, used only during the simulated shuttle (SSV-SIM) configuration operation, are the three round pushbutton switches located at the lower right side of the panel.

The functions controlled by the toggle switches are indicated by the physical position of the switch. The functions controlled by the pushbutton switches are active if the switch is illuminated. Operation of a pushbutton switch usually (there are some exceptions) activates the mode controlled by that switch if the mode was inactive and deactivates the controlled mode if it was already active.

The overall function of the MSP is explained below in terms of examples for (1) CV-990 MSP controls, and (2) SSV-SIM MSP controls. The first example shows how the pilot uses the MSP to select and operate a typical mode, "altitude hold," in the conventional (CV-990) transport configuration of the SS-FTS.

CV-990 Controls. - Once the pilot selects the conventional jet transport configuration by placing the [CV-990/SSV-SIM] switch in the [CV-990] position, there are several methods by which he may choose to fly at a constant altitude with the digital autopilot. These methods are: (1) flight director mode with input through the normal aircraft controls; (2) flight director mode with input commands through the side stick controller; and (3) fully automatic control. A description of the pilots use of the MSP to fly the altitude hold mode with each of these methods follows:

1. Altitude hold with normal aircraft controls. To fly the flight director mode with manual inputs through the normal aircraft controls, the pilot's actions are as follows:
    a. Engage the yaw damper by placing the [YAW DAMPER] switch to the [ON] position. This step is optional because the autopilot is not engaged for this method of altitude hold.

b. Press the [ALT HOLD] switch. This switch will illuminate green indicating the system is in the altitude hold mode and that the flight director commands are being generated.

c. Use the normal aircraft controls to follow the flight director commands to maintain the constant altitude.

d. The pilot disconnects the altitude hold mode by again pressing the [ALT HOLD] switch. This action extinguished the switch light and stops the computation of the altitude hold flight director commands.

2. Altitude hold with side-stick controller. To fly the flight director mode with inputs through the side-stick controller the pilot takes the following actions:

a. Engage the yaw damper by placing the [YAW DAMPER] switch to the [ON] position.

b. Engage the autopilot by placing the [AUTOPILOT] switch to the [ON] position. This action illuminates both segments of the [ROLL PITCH] switch indicating that the side stick is active and can be used to control the aircraft in both pitch and roll. The pilot's "yoke" will follow the control surface motions.

c. Press the [ALT HOLD] button. The button will illuminate green, indicating that the system is in the altitude-hold mode and that the flight director commands are being generated.

d. Use the side-stick controller to follow the flight director commands to maintain the constant altitude.

e. The pilot disconnects the altitude hold mode by pressing the [ALT HOLD] switch a second time.

3. Fully automatic altitude hold. The pilot takes the following actions:

   a. Follow the procedure above to obtain altitude hold control with the side-stick controller.

   b. Press the [AUTO] button. This action will illuminate the [AUTO] button to indicate that the selected digital autopilot function [ALT HOLD] is being performed automatically. At the same time, the [PITCH] portion of the [ROLL PITCH] button will be extinguished to indicate that pitch commands can no longer be input to the system through the side-stick controller. The illuminated [ROLL] segment indicates that the aircraft can still be controlled in roll with the side-stick.

   c. When the pilot disconnects the altitude hold mode as described above, the [AUTO] button will also extinguish since there is no further aircraft control function to be performed automatically. As the [AUTO] button is extinguished, the [PITCH] segment of the [ROLL PITCH] will be illuminated to indicate that the aircraft can again be controlled in pitch and roll through the side-stick.

SSV-SIM controls. - The second example involves MSP controls used in the simulated shuttle approach and landing, which include the three toggle switches and the six pushbutton switches on the right side of the panel. The switches can be functionally divided into two groups: (1) aircraft mode control switches, and (2) special SSV-SIM control switches. The pilot use of the MSP switches in the [SSV-SIM] configurations is briefly described below.

Aircraft mode control switches: Once the pilot selects the simulated shuttle configuration by placing the [CV-990/SSV-SIM] switch in the [SSV-SIM]

position, he has the same options for flying the simulated shuttle energy management approach and landing as described for the [CV-990] configuration. The control method selected by the pilot is a function of three switches: (1) [YAW DAMPER] switch; (2) [AUTOPILOT] switch; and (3) the [AUTO] switch. These switches, which perform the same functions in both the CV-990] and the [SSV-SIM] configurations, are interlocked and must be engaged in the order listed above. The status of these three MSP switches are listed below for each of the three control methods.

1. Flight director mode with input commands through the normal aircraft control.
   a. [YAW DAMPER] switch; optional, may be [ON] or [OFF]
   b. [AUTOPILOT] switch [OFF]
   c. [AUTO] switch extinguished
2. Flight director mode with input commands through the side-stick controller. Note that when the side-stick controller is used in the simulated shuttle configuration, both the roll and pitch axes are always active.
   a. [YAW DAMPER] switch [ON]
   b. [AUTOPILOT] switch [ON], resulting in the [ROLL PITCH] switch being illuminated
   c. [AUTO] switch extinguished
3. Automatic control
   a. [YAW DAMPER] switch [ON]
   b. [AUTOPILOT] switch [ON]
   c. [AUTO] switch illuminated, resulting in the [ROLL PITCH] switch being extinguished

During the automatic control mode of the simulated shuttle approach and landing, the aircraft attitudes and direction are controlled by the system computer. However, certain functions needed during the approach are not automated, and the pilot assists the system in the performance of these actions. For example, neither the aircraft speed brake deployment nor the radio navigational aids tuning is automated. When the navigation receivers require tuning, speed brake deflection changed, etc., the system displays the appropriate messages for the pilot on the status panel.

Special SSV-SIM control switches: The MSP contains three round pushbutton switches that are used exclusively in the SSV configuration: (1) [SEL], (2)[INS], and (3) [R/D]. The functions of these three switches are briefly outlined below.

1. [SEL] (navigation configuration selection). After the [SSV-SIM] configuration is selected, but before the navigation equations can be initialized, the system must know which electronic aids to use during the navigation and where the aids are located with respect to the intended touchdown point. Normally, this information is prestored in the computer memory and the pilot simply selects the appropriate prestored navigation aid configuration after engaging the system. For example, in recent flight tests, the prestored navigation aid configuration at Edwards AFB used two specific DME stations (DME/DME) first; then one DME and the Edwards' localizer (DME/LOC); and last, the Edwards localizer and glide slope (LOC/GS) for the final phase of the landing. However, the pilot could elect to press the [SEL] button and follow the computer procedure to define a

new navigation aid configuration. This will include the type of navigation aids (DME, VOR, LOC, etc.) and their locations with respect to the runway coordinates. The [SEL] mode will be de-energized ([SEL] button extinguished) once the proper data are entered through the data entry panel. Pressing the [SEL] switch a second time will not deactivate the mode.

2. [INS] (inertial navigation system). During the simulated shuttle approach, the system normally uses blended radio-inertial data for navigation computation. When the radio navaid information is not available, the system will navigate using INS data only. When navigation is being determined only by INS data, the [INS] switch flashes green.

When the [SSV-SIM] configuration is first selected, the system goes through a process of initializing the navigation equations based upon the available data from the INS. Once the equations are initialized, the [INS] switch flashes, indicating to the pilot that he may select blended radio-inertial navigation.

When the pilot pushes the [INS] switch, the flashing light will be extinguished and the system will begin using blended radio-inertial data for the navigation computations.

Once the system is using the navaid data in the navigational computations, the flag or valid* signals of the required navaids are continually checked by the computer. If the valid of a required

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* Most navigational aids contain internal monitors that generate flag or valid signals. These flag or valid signals indicate when the navigational quantities associated with the equipment are reliable.

signal ceases to be present in the computer, the system assumes that the required navaid signal is no longer valid. The navaid signal is then removed from the navigational computation and the system reverts to navigation by INS data only. The [INS] switch flashes and a message is displayed to the pilot on the status panel.

The message advises the pilot which required signal is not available so that he may take the appropriate action. For example, if a required localizer signal valid were not present, the message would be "TUNE TO LOC." The pilot would check the proper radio receiver to see that the localizer signal was tuned in and that the valid or flag signal was present on the HZ6F. At the same time, he would keep in mind that, discounting system failures, the valid of a required navaid may not be present for at least two reasons: (a) the navaid signal is weak in the area of the aircraft present position, and (b) the system is changing navigation modes and now requires a different navaid for its calculation.

Once the required flag or signals are present, the message of the status panel will disappear. At this time, the pilot can return the system to blended radio-inertial navigation by pushing the blinking [INS] switch. Once the radio-inertial navigation has been reestablished, the flashing light will be extinguished.

3. [R/D] (raw-data) mode. This switch enables the pilot to select a raw-data backup mode. The raw-data mode can be selected, by

pushing the [R/D] switch, whenever the system is in the [SSV-SIM] configuration with the control by the side-stick. When the raw-data mode is selected, the [R/D] switch illuminates and the pilot receives steering commands on the glideslope and expanded localizer scale of the HZ6F flight director. The raw data mode is discussed further in the navigation section. The pilot may return to the normal flight director mode and extinguish the [R/D] switch at any time by pressing the [R/D] switch again.

The Approach Progress Display

The approach progress display (APD) provides the pilot with the mode situation of the system by annunciation of the critical submodes (fig. 11). The six indicators of the left side of the panel are associated with the CV-990 configuration. The ten indicators to the right of the panel are used for the SSV-SIM configuration. A [PANEL TEST] switch in the upper right corner provides for ground or inflight testing of the operation of all indicator lamps and associated electronics for the APD, the status panel, and the mode select panel. The [DIM] switch in the lower right corner provides for dimming the lights on all indicators and switches on all display SS-FTS panels during night time operation.

The six CV-990 indicators provide for annunciation of the normal CV-990 controlled approach and landing operation. The [LOC/VOR] and the [G/S] indicators illuminate amber when the mode is armed and green when the mode is in the capture of tracking phase. The [DECRAB] and [FLARE] indicators illuminate only green when the mode is active. The [REV CSE] (reverse course) and the [DH] (decision height) indicators are not presently used. The [LOC/VOR] indicator also annunciates that the system is in the [VOR NAV] mode as controlled by the mode select panel.

In the SSV-SIM configuration, all inflight operating modes for initiation of an approach through decrab are annunciated by means of the ten indicators. The five indicators in the top row are used to indicate events connected with the lateral or horizontal guidance of the aircraft; the five indicators in the bottom row are associated with the vertical guidance. The [LOC] indicator has arm and engage lights, but all others have only an engage light. The symbols and their respective lateral and vertical mode functions are listed in table 3 and discussed in the section on guidance.

Data for the annunciation of all modes for both the CV-990 and the SSV-SIM displays are under complete software control and are transmitted with the 1819A computer via the data adapter to the status panel. The electronics required to operate APD is contained within the status panel.

The indicators are illuminated when the associated mode is armed or captured and will stay illuminated until the aircraft is no longer operating in that mode.

Side-Stick Controller

When the system is in the [ROLL PITCH] modes, roll and pitch attitude rates are commanded proportional to the displacement of the side-stick controller. When the side stick is returned to its spring-centered detent position in either control axis, zero attitude rate is commanded in that axis and the existing attitude is held.

The side-stick controller was not designed specifically for the SS-FTS. Physically, it is a very simple device. The base contains two potentiometers, which are mechanically linked to the controller handle to supply the rate command signals as the handle is deflected.

The handle contains a thumb switch and a trigger switch. The thumb switch, when pressed, changes the system mode from the [AUTO] to the [ROLL PITCH] mode. The trigger switch is not used. The side-stick must be in its detent center positions for the system autopilot to be engaged.

Rack-Mounted Equipment

The following major items of SS-FTS equipment are mounted in an experimenters' equipment rack (fig. 12) in the main cabin of the aircraft: (1) the 1819A digital computer, (2) the data adapter, (3) the power control unit, and (4) the rate gyro assemblies. The rack also contains a system power control and monitoring panel, which includes the main system power switches and circuit breakers and a series of indicator lights for monitoring the various valid signals of the system. The rack, easily removed or installed, contains a blower to supply cooling air to the rack-mounted components. The forward side of the rack contains two sets of quick disconnect electrical connectors. One set is used to interconnect the rack equipment with the aircraft and other SS-FTS equipment. The second set, wired in parallel with the first, is used for monitoring and testing. The rack location with respect to other SS-FTS components is shown in figure 13.

1819A Digital Computer

The 1819A digital computer controls the system operation, interfacing with the pilot and all system hardware through the data adapter. Main characteristics of the 1819A are listed in table 4. The computer is contained in a single ATR case and weighs approximately 23 kg (50 lb).

Although the computer basic word length is 18 bits, double precision operation provides a 36-bit word capability. The organization of the central processor and the 2-μsec memory cycle time provide sufficient speed for real-time calculation in the flight environment. The party line input/output channels connect to the data adapter to provide data flow between the computer and the other system components.

The computer contains hardware and software provisions for self-testing--BITE. In the case of hardware, "BITE" stands for built-in-test-equipment. BITE is also used in referring to built-in software test programs. The BITE software program is contained in nondestruct read-only memory. The 1819A BITE performs two different functions. First the BITE portion of the system preflight program exercises all computer instructions that would be executed in a typical airborne program. The second BITE function is to provide continuous monitoring of vital internal functions of the computer without interrupting the normal operational status of the computer during systems operation.

The inherent flexibility of the programmable digital computer is enhanced by the integrated modular software package, which provides all computation for navigation, guidance, control and display. The basic computational cycle rate for the computer program is 50 msec. The total computer memory space used for the entire program including preflight programs, is about 11,000 (18-bit) words. The major subroutines perform the following functions:

1. Guidance. The system contains two separate guidance programs: (a) a program to fly space shuttle trajectories from high altitude to touchdown, and (b) a program to perform CV-990 autopilot functions.

2. Navigation. This function is for space shuttle modes only. The navigation program estimates aircraft position using combinations of DME, VOR, ILS and inertial information (INS).
3. Control. This routine performs basic inner-loop control, both pitch and lateral/directional, and provides vehicle stabilization and control from guidance commands.
4. Displays. This routine provides basic and command information to the status panel, mode select panel, data entry panel, and approach progress and display panel.
5. Input/output. This routine provides for complete input and output conditioning of data from all sensors, to servos, displays, digital data acquisition system (ADDAS), aircraft instruments, etc.
6. Preflight test. A complete preflight test extensively checks aircraft sensors such as: the air data computer, INS computer, displays, ADI, side stick, and others. Failed test and diagnostic numbers are indicated on the status panel.
7. Inflight monitoring. This routine performs inflight monitoring of all discretes, valids, and servo positions (pitch, roll, and yaw).

Several previously mentioned features closely associated with the computer are: (1) the modular nature of the program allows one subroutine to be modified or changed with no effect on other subroutines; (2) pilot access to the digital computer program parameters inflight allows a rapid evaluation of a series of program gains during a single flight; and (3) use of the ground-based Validation Facility aids in developing software programs and debugging programming changes.

Data Adapter

The data adapter is a multipurpose unit that provides the required interface between the digital computer and the other airborne equipment. It not only controls the information transfer between subsystems, sensors, and displays, and the digital computer, but also provides the necessary signal conditioning for all associated equipment. The data adapter provides multiplexed A/D, D/A, and D/D conversions.

Figure 14 shows the general interconnections of the data adapter with the other system equipment. The figure is divided into three sections: (1) pilot controls and displays, (2) navigational aids and aircraft sensors; and (3) control surface interface and data recording. Note that the data adapter contains provisions for a second computer and certain navaids that have not yet been flight tested. The second computer was intended to provide additional computational capability and could be used to provide Kalman filtering or other processing of the navigational data.

In addition to the conventional navigational equipment (DME, ILS, etc.) used in the simulated shuttle system described in this report, the data adapter has provisions to accept: (1) a microwave scanning beam landing guidance system (SBLGS), based on the ARINC SC 117 landing system; (2) an ARC/Cubic precision landing system (ACPRS), which supplies ranges from the aircraft to three ground transponders with the accuracy in the order of a few feet; and (3) the NASA electronic interface unit (EIU), which provides integrated INS accelerometer signals in digital form.

Functionally, the data adapter can be divided into five subsystems, each concerned with converting information from one form to another: (1) analog and discrete input channel; (2) digital input channel; (3) analog

and discrete output channel; (4) digital output channel; and (5) master/ slave intercomputer interface. These subsystems are completely independent, operate asynchronously, and use a common power supply and clock. The power supply, which furnished all the necessary voltages, contains monitoring and regulating provisions to prevent improper operation. The clock, a crystal controlled oscillator, supplies all the data adapter timing pulses for data processing and is independent of the 1819A computer clock. Although the data processing within the data adapter is asynchronous with the computer clock, the computer clock does control the timing of all data transfers into and out of the data adapter.

Analog and discrete input channel subsystem. - This subsystem contains all the circuitry necessary to convert the ac and dc analog and discrete signals into a binary format for suitable transfer to the digital computer. Each input signal is buffered, filtered, scaled, and demodulated, as required, and then processed in a fixed sequence by the multiplexer and the A/D converter. converter. The A/D converter is a high-speed successive-approximation type, which converts the 10V dc inputs to 12-bit binary words with an accuracy of 0.1 percent. The throughput rate for converting and inputting the word into the computer is 225 μsec. Since the ac and dc analog inputs use only 12 bits of the available 18-bit computer words, the discrete input signals are combined with the analog input signals to save storage.

Digital input channel subsystem. - This subsystem handles all of the parallel and serial digital inputs to the data adapter. Each data word is tagged with a four-bit identification code to assure proper processing, and entered as a parallel word into the computer.

Analog and discrete output channel subsystem. - This subsystem converts the 18-bit parallel binary data from the computer to analog form as required

by the using equipment. The 18-bit binary words contain 10-bits of analog data plus discrete data. The subsystem unpacks the discretes and the analog data. The unpacked data are converted to the output voltage levels and distributed to the using system equipment. The subsystem also transfers digital data from the 1819A computer to the ADDAS recording system. There are 129 16-bit data words transferred to the recording system every 50 msec.

Digital output channel subsystem. - This subsystem accepts 36-bit parallel binary data from the computer, converts it to serial data format for transfer to the status panel and other system units. The serial data are transmitted at a 50-kHz data rate to the using subsystem asynchronously with the computer timing.

Master/slave intercomputer interface. - This system provides for high-speed 18-bit parallel data transfer between the master 1819A computer and the slave 1819A computer. Data transfer is bidirectional on an interrupt basis. An 18-bit parallel storage register is provided to temporarily store data words while waiting for the computer to honor data transfer requests.

Power Control Unit

This multifunction unit provides the interface between the digital computer, via the data adapter, and the control surfaces of the aircraft. Its functional subsystems are: (1) servo amplifiers, which drive the existing aircraft autopilot rudder, aileron, and elevator control surface servo motors; (2) a trim coupler, which controls the position of the horizontal stabilizer; (3) a yaw damper subsystem; and (4) a power-supply subsystem.

Servo amplifiers. - A servo amplifier subsystem contains the three servo amplifiers. These amplifiers interface with the existing servo motors to form feedback control systems, which position the three aircraft control surfaces--rudder, ailerons, and the elevator--in response to position commands from the computer. The yaw servo amplifier also accepts command signals from the yaw damper subsystem. The servo amplifiers accept the control surface position and rate feedback signals, and the servo control loops are closed without the need to run the feedback signals through the data adapter to the computer. This hardware closure of the feedback loops avoids the large computational time that would result from closure of the rate and position loops in the computer software.

Trim coupler subsystem. - The autopilot system trims the elevator by changing the angle of incidence of the horizontal stabilizer. When the elevator is out-of-trim while under autopilot control, this subsystem sends trim signals to the horizontal stabilizer. Elevator out-of-trim conditions are determined by monitoring the average output of the pitch servo amplifier. When the average output of the pitch servo amplifier exceeds a preselected level, corrective trim commands are sent to the aircraft stabilizer trim actuator. The SS-FTS trim coupler incorporates proportional control of the trim rate through duty cycle modulation. The proportional control allows a more accurate trim rate control than available with the basic aircraft trim rate system.

The system includes a trim warning monitor, which (1) detects failure to correct an out-of-trim condition due to rate limiting or a failure of the horizontal stabilizer trim system, and (2) transmits a signal to the auto pilot trim indicator on the pilot's instrument panel.

Yaw damping subsystem. - The yaw damping subsystem provides for accelerometer yaw damping or rate gyro yaw damping. If the SS-FTS data adapter or digital computer is disconnected, the yaw damping is equivalent to the SP-30 accelerometer yaw damping. However, when the SS-FTS is operational the computer uses the rate gyros in addition to the aft lateral accelerometer to generate the necessary rudder servo damping commands.

Power supply subsystem. - This subsystem supplies the dc voltages required by the status panel, mode select panel, data entry panel, and approach progress display. Monitoring circuits within the subsection provide protection against the generation of over voltage within the power supply.

Rate Gyro Assemblies

Necessary aircraft rate commands about three axes are supplied by two rate gyro assemblies: (1) a yaw/roll rate gyro assembly includes separate yaw and roll gyro channels. Each channel includes a rate gyro, demodulator, and output amplifier, along with circuits required to utilize the rate gyro self-test torquer and the gyro spin motor speed monitor. Each channel provides a rate gyro output to the SS-FTS system, and a resistor isolated output for use by the data acquisition system. The yaw channel has an additional output to drive the rate of turn cue on the flight director indicator. The pitch rate gyro assembly provides a single gyro channel identical to the roll channel.

For test purposes, each rate gyro includes dc permanent magnet torquer, which torques the gyro gimbal proportional to the dc voltage applied to the torquer coil. Electronics in the unit provides a current to torque the gyro to 5°/sec equivalent rate in response to a 15-V discrete self-test

signal from the data adapter. Each gyro includes a spin motor rotation monitor detector that will drop the gyro valid voltage from the unit when the spin motor rpm is less than 75 percent of nominal. The rate gyro characteristics are as follows:

Full scale rate	±40°/sec
Sensitivity full scale*	±5 V ±5%
Acceleration sensitivity	0.05 deg/sec/g
Threshold and resolution	0.08°/sec
Angular momentum	30,000 gm-cm^2/sec
Damping ratio	0.5 to 0.9
Spin motor synchronization time	30 sec
Hysteresis	< ±7.5 mV
Null (ac rms)	< ±25 mV

AIRCRAFT FLIGHT CONTROL INTERFACE

The pilot and copilot controls--that is, the control column and the rudder pedals--remain connected to the control surfaces by cable. As the SS-FTS moves the control surfaces, the pilot's controls follow, allowing the pilot to monitor the system action. For safety's sake, the servo amplifier output from the power control unit is limited in each axis to approximately one-half of the total rated servo motor power. The limit allows the safety pilot or the test pilot to overpower and automatically disconnect the SS-FTS output by moving the manual controls.

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* Tolerance does not include effect of power supply voltage and frequency variation.

The maximum stabilizer trim rate achieved by the SS-FTS autopilot is higher than that obtained with the standard SP-30 autopilot. The maximum rate is equal to that obtained by the pilot's manual "beep" trim system. The higher trim rate system was shown to be necessary for the simulated shuttle approaches. The faster trim rate was achieved by disabling the mechanical and hydraulic rate limits which are normally engaged when the autopilot is engaged.

The stabilizer trim rates are shown below for the standard SP-30 autopilot, the SS-FTS autopilot, and the pilot's manual "beep" trim system. When the autopilot is disengaged, the stabilizer trim is achieved by the normal beep trim switch on the control column wheel.

		Nominal Stabilizer Trim Rates	
Autopilot Status	Flap Position	Fixed Rate Standard SP-30 Autopilot Degrees/Second	Maximum SS-FTS Autopilot Degrees/Second
Engaged	up*	0.077	0.25
Engaged	down	0.077	0.53
Disengaged	up*	0.25	0.25
Disengaged	down	0.53	0.53

The inflight monitoring system assures that the aircraft control surface positions agree with the computer commanded positions. This is done with a servo monitor (fig. 15) on each axis. The computer-commanded surface position passes through the D/A converter to the surface servo system. The actual surface position and rates are fed back into the computer through the A/D converter for comparison with the original computer command. If the servo doesn't meet the required tolerance, the system is automatically

* Flaps are considered up when deployed three degrees or less.

disengaged. The D/A and the A/D accuracy are checked at the same time by returning the output of the D/A to the computer through the A/D for comparison with the original signal output through the D/A.

NAVIGATION AND GUIDANCE

Navigation and guidance are two of the major tasks of the system software and consists of specialized subroutines. The navigation and guidance subroutines can be tailored to the needs of the experimenter so long as the necessary navaids are available and the operational constraints of the aircraft are observed. This section contains very brief descriptions of the navigation and guidance subroutines used in the system to simulate the space shuttle approach. A more detailed description of the navigation, guidance, and control concepts used in the simulated shuttle flight tests can be found in references 7 and 8.

Navigation

The navigation portion of the main program supplies the guidance system with estimates of the required aircraft states, such as position and velocity. Since the measured data necessary to compute the aircraft states contains noise detrimental to the system performance, filters are used to improve the state estimates.

Figure 16 displays a typical trajectory in a simulated shuttle test run and identifies the navigational aids used by the SS-FTS navigation system during various portions of the trajectory. The inertial navigation system is used at all times to blend the radio and inertial data. The navigation system first determines the aircraft altitude estimate and then uses this estimate in all calculations to determine the unfiltered horizontal

aircraft positions with respect to the runway. As shown in figure 16, the trajectory begins at point A with the energy management portion of the flight. This phase is designed to align the vehicle with the runway heading at the top of a two-segment approach path point E with a velocity of about 230 knots indicated air speed.

During the energy management phase the horizontal navigation system is in a DME-DME-NAV mode and determines the unfiltered aircraft positions using two DME ranges, one VOR bearing, and the altitude estimate. The VOR bearing is used only to resolve the ambiguity present from the two range solution of position. When the aircraft completes the final turn of the energy management section of the flight, point E, the aircraft is approximately aligned with the runway centerline. The navigation system remains in the DME-DME-NAV mode until the aircraft descends to an altitude of less than 61,000 m (20,000 ft) AGL and is within 37 km (20 nm) of the glide-slope intercept point.* At this time, the aircraft is nominally on the steep glide slope 1 mi closer to the runway than point F.

The navigation mode now changes from DME-DME-NAV to DME-LOC-NAV, in which the aircraft unfiltered position calculations are based on a single DME range, the ILS localizer deflections, and the altitude estimate. The navigation system changes to the final mode as the aircraft prepares to transition from the steep glide slope to the ILS glide slope at point G. In this final horizontal navigation mode, GS-LOC-NAV, the SS-FTS system uses ILS glide slope and localizer deviation data and the altitude estimate to compute the unfiltered aircraft positions. The system remains in the GS-LOC-NAV mode through final flare and after touchdown until the autopilot is disconnected. However, the system stops using the downrange position measure-

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* The glide-slope intercept point is the point at which the ILS G/S intersects the runway centerline.

ment at the start of the final flare and the lateral measurement at the initiation of the decrab.

Guidance

The guidance system must compute the desired or reference flight path and provide the required command signals to the aircraft control system to fly the reference path while observing constraints imposed on the system by the experimenter and the maneuvering capability of the aircraft.

The guidance modes are most easily understood by considering the various phases of the typical simulated shuttle approach trajectory shown in figure 17. The test run begins at Point A at approximately 11,300 m (37,000 ft) above sea level. Point A must be within the energy window shown, which is a cardioid, approximately 64x48 km (40x30 mi).

The energy management phase maneuver is based on an imaginary vertical cylinder, the runway centerline plane and an outbound radial plane. The vertical cylinder is about 14.8 km (8 nm) in diameter and its axis is on the runway centerline extension. The horizontal projection of the vertical cylinder is called the R-zero target circle. The outbound radial plane is tangent to the vertical cylinder and intersects the runway centerline extension at a 20° angle. During the energy management phase of the flight, the aircraft flies to the target circle (point B), around the cylinder to the outbound radial plane, along the outbound radial plane and through a final turn to point E of the runway centerline plane.

Regardless of its initial position and direction at the start of the run, the guidance mode commands the vehicle to fly a heading that is tangent to the target circle and will permit a smooth transition to a

clockwise path around the target circle. The length of the path along the outbound radial plane is a function of the vehicle energy. The system determines when the final turn should be started based upon the current aircraft energy and the predicted radius of the final turning circle, which is simultaneously tangent to the outbound radial and the runway centerline extension.

The straight-in approach begins at the end of the final turn, point E. This lateral mode guides the aircraft along the runway centerline. Although the ILS localizer signal is used during this mode, the guidance parameters are derived from the navigation system. Thus, the guidance system is not a beam rider, although the results are similar when the ILS localizer signal is being used.

The steep glide-slope mode, annunciated by the steep G/S indicator on the approach progress display, guides the aircraft down the prescribed 10° glide slope from the end of the energy management phase to the beginning of the first flare at about 427 m (1400 ft). During the steep glide-slope phase, the aircraft accelerates from a nominal indicated airspeed of 230 knots to a nominal equilibrium glide speed of 305 knots. This acceleration results from the normal tendency of the vehicle velocity to converge to a constant calibrated airspeed as the flight path angle is constrained. To compensate for any airspeed variations from the nominal caused by winds, the guidance system commands a speed brake setting, via the status panel, when the aircraft is 760 m (2500 ft) above the ground. The speed brake command is a function of aircraft weight and inertial velocity and is resolved into 5° increments to correspond with the speed brake control accuracy.

The first flare, point F-G, provides a smooth open-loop transition from the steep to the shallow glide path with a maximum acceleration of 1.25 g vertical acceleration.

The shallow glide-slope mode begins as the first flare ends, near point G. During this mode, the aircraft system tracks the ILS glide-slope beam until it reaches a height of about 18 m (60 ft) above the runway. The aircraft decelerates at about two knots per second during this phase of the flight.

The system switches to the final flare mode at an altitude (nominally about 18 m) that is a function of the aircraft altitude and altitude rate. The final flare provides a smooth exponential transition from 2.5° glide slope to touchdown. The guidance system uses altitude rate and vertical acceleration feedback during the final flare maneuver to reduce the dispersion on the altitude rate at touchdown. A nominal altitude rate of 1 m/sec is acquired when the aircraft is about 2.5 m (8 ft) above the runway, and maintained until touchdown.

The final lateral guidance mode, decrab, is entered when the aircraft is about 2.5 m (8 ft) above the ground. During the decrab mode, the aircraft is aligned with the runway heading for touchdown. At touchdown, the pilot assumes manual control of the aircraft and disengages the system. The nominal indicated airspeed at touchdown is 175 knots with variations between 150 and 200 knots.

A simplified SSV initial engagement module is incorporated in the software to provide the flexibility of engaging the SSV mode at lower altitude conditions. This module provides for automatic initialization of the appropriate pitch/lateral guidance and navigation modes, which eliminates the necessity of automatically sequence through all modes in the normal SSV

trajectory from high altitude. Mode selection is based on the following three variables: (1) position in runway coordinates, (2) altitude above runway, and (3) vehicle heading relative to the runway.

Raw Data Guidance

While the space shuttle will surely have some type of backup or raw data guidance, the specific type will not be known until the principal guidance equipment and techniques have been selected. The raw data mode of the SS-FTS system is designed to evaluate one technique for backup guidance. The raw data mode, available only using the flight director in the simulated shuttle configuration, allows the pilot to fly the vehicle in a trajectory similar to that of the normal guidance modes. The pilot manually controls the aircraft to center the cross-bars on the flight director. The raw data mode uses simplified flight path guidance techniques with straight-line approximations. The raw data mode approximates the guidance that might be obtained with an elementary analog area navigation system.

Not yet evaluated inflight, the raw data mode described above is just one of many such modes that could be programmed and evaluated with the SS-FTS flight research facility.

FLIGHT DATA RECORDING

The Airborne Digital Data Acquisition System

Flight data are recorded by the Airborne Digital Data Acquisition System (ADDAS), which is part of the CV-990 aircraft system. The ADDAS incorporates a Hewlet-Packard 2116B computer and 2150B extender unit, which

are general-purpose digital computers suited for data processing and analysis, as well as the data-acquisition task. Considerable flexibility of the ADDAS is achieved through a variety of peripheral devices.

The system accepts both analog and digital inputs. Present capability allows for 48 analog inputs sampled at rates of 20 samples/sec, 12 analog inputs sampled at one sample/sec, 34 quantities of BCD data from the INS, 20 groups/sec of 129 digital words from the Sperry computer, and 48 I/O channels for interfacing with peripheral devices and other computers.

The internal computer "clock" is manually synchronized with real-time (i.e., WWV time signal). Accuracy is better than 0.1 msec in 24 hr. This time signal is recorded on the data tapes in days, hours, minutes, and seconds.

Figure 18 is a diagram of the ADDAS system used during CV-990 simulated shuttle flight tests. The types of data measured are discussed below. Sufficient measurements are provided so that the SS-FTS system status, performance, and operating conditions (normal, failed) can be monitored onboard in real-time or reconstructed from recorded data for postflight analysis.

Data Tape Format

All raw measurements are recorded on a pair of digital magnetic tape units. The two unit arrangement assures continuous recording by eliminating loss of data incurred while chaning reels in a single unit system. The tape records are compatible for playback into an IBM 360 computer. Observer comments can be recorded on the magnetic tape along with the data readings via a selectric typewriter. Each tape record contains one second of data, which includes the following information:

Number of words	Information
2	Flag word (indicates presence of selective typewriter comments)
2	GMT time
68	INS data stream
40	Selective typewriter comments
800	Multiverter data input as 40 channels, 20 times/sec
24	Crossbar scanner data input as 12 channels every second (each quantity uses two words)
2709	Sperry 1819A computer data input as 129 words, 21 times/sec
3645	Total words

Quick-Look Data

A preselected number of data measurements may be displayed in engineering units on the high-speed line printer and on the eight-channel strip recorder allowing "quick-look" evaluation while the flight is in progress. Calibration curves can be incorporated in the ADDAS computer software package. Real-time printout and strip-chart recordings provide information for trouble-shooting, system optimization, and preliminary performance evaluations.

CONCLUDING REMARKS

The Simulated Shuttle Flight Test System (SS-FTS), installed in the NASA/ARC CV-990, was developed to allow the flight evaluation of advanced landing approach concepts under consideration for the Space Shuttle Vehicle. This flexible facility has potential application to the study of a broad

spectrum of terminal area problems, as well as research on noise abatement and energy management approach techniques for conventional jet transports.

The SS-FTS digital avionics features a general-purpose digital computer and is presently programmed to provide two major configurations: (1) a digital autopilot for use with jet transport conventional modes including autoland, and (2) a simulated shuttle test bed for terminal area research. The digital autopilot replaces the normal SP-30 analog autopilot of the CV-990. The simulated shuttle configuration is capable of aircraft navigation, guidance, and control from high altitude to touchdown with the aircraft engines at idle. Both configurations feature automatic or flight director modes.

The digital system includes sensors and navaid equipment to determine the aircraft state in three spatial dimensions and the three velocities. The navigation emphasis is placed on inertial navigation system data augmented with conventional navaid data. The system is equipped to accept conventional ILS, VOR/DME, radio altimeter, magnetic heading and air data computer information. Provisions are included to accept signals from a microwave scanning beam landing guidance system and multilaterial beacons.

Safety features include:

1. Semiautomatic preflight equipment check
2. Capability of pilot to override the system at anytime by use of the control column
3. Limited control authority (glide slope to 15° or less, bank angles to less than 45°)
4. Automatic inflight monitoring of critical system functions

Sufficient system and aircraft state measurements are made and recorded inflight to evaluate the status, performance, and operating conditions of

the system for postflight analysis. Certain preselected measured data are available onboard in real time for monitoring the system performance.

System flexibility is derived chiefly from the use of a programmable general-purpose digital computer. Various concepts and mechanization techniques for terminal area navigation, guidance, and control can be investigated by reprogramming the computer. The system is most easily adapted to research projects that can be initiated by reprogramming the computer while utilizing the presently available navaids and aircraft sensors.

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9. Gaylor, Randall: Flight Test System for Study of Space Shuttle Vehicle Guidance and Navigation Concepts. Final Report. Publication No. 71-0386-00-00, Sperry Flight Systems, Phoenix, Arizona. September 1973.

10. Advisory Circular No. 20-57A, Automatic Landing Systems, 12 Jan. 1971, Dept. of Transportation, Fed. Av. Adm.

Table 1. Physical Characteristics of the CV990

Fuselage -	
Maximum width, m (ft)	3.51 (11.50)
Maximum height, m (ft)	3.78 (12.42)
Length, m (ft)	42.60 (139.75)
Wing -	
Incidence (root), deg	4
Aerodynamic span, m (ft)	35.97 (117.99)
Area, m^2 (ft^2)	209 (2250)
Root chord, m (ft)	8.88 (27.15)
Tip chord, m (ft)	2.69 (8.83)
Mean aerodynamic chord, m (ft)	6.34 (20.81)
Dihedral, deg	7
Aspect ratio	6.2
Leading-edge sweep, deg	39
Horizontal tail -	
Area, m^2 (ft^2)	39.6 (426.55)
Dihedral, deg	7.5
Leading-edge sweep, deg	41
Span m (ft)	11.80 (38.74)
Aspect ratio	3.52
Vertical tail -	
Area, m^2 (ft^2)	27.4 (295)
Sweep at 30-percent chord, deg	35
Span, m (ft)	6.45 (21.17)
Aspect ratio	1.52
Aileron -	
Area, m^2 (ft^2)	2.78 (29.97)
Span, m (ft)	2.93 (9.62)
Maximum travel, deg	±15
Inboard spoiler -	
Area, m^2 (ft^2)	1.65 (17.8)
Mean aerodynamic chord, m (ft)	0.85 (2.8)
Maximum travel, deg	75
Outboard spoiler -	
Area, m^2 (ft^2)	3.86 (41.51)
Mean aerodynamic chord, m (ft)	0.95 (3.11)
Maximum travel, deg	60

Table 2. - Central Features of the SS-FTS

- A hieracy of operating modes
- Easily modified control laws and interlocks
- Modular software packages
- Many navaids available
- Inertial smoothing of navaid data
- Predetermined parameters can be changed in flight
- Flexibility in pilot displays
- In flight systems monito ing
- Comp!ete preflight test capability
- Use of specially designed ground-based simulation facility to validate the software package (Software Validation Facility).

Table 3. - Guidance Modes and Corresponding Approach Progress Display Symbols

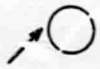
APD Symbol	Pitch Guidance Mode
α	1. Operational L/D. Maintain the operational L/D to maximize aircraft range.
STEEP G/S	2. Steep glide slope. Maintain the aircraft on the reference ten degree glide path.
FIRST FLARE	3. First flare. Transition from the steep glide slope to the shallow glide slope, 1.25 g maximum.
SHLW G/S	4. Shallow glide slope. Maintain aircraft on ILS glide slope beam.
FINAL FLARE	5. Final flare. Transition from shallow glide slope to touchdown attitude with exponential flare.
	Lateral Guidance Mode
	1. Target circle acquisition and track. Guides aircraft to target circle and then around the circle to the 20° radial.
	2. Radial track. Guides the aircraft out a 20° radial while computing the beginning point of the final turn.
FINAL TURN	3. Final Turn. Makes a procedural turn from the 20° radial track to intersect simultaneously the runway centerline and the reference steep glide path.
LOC	4. Localizer. Maintain the aircraft on the runway centerline by using the ILS localizer signals.
DECRAB	5. Decrab. Align the aircraft with the runway just prior to touchdown.

Table 4. - 1819A Computer Characteristics

-Two microsecond cycle time
-1K X 18 bits read only memory - expandable to 4K
-16K X 18 bits core memory - expandable to 32K
-Parallel operation
-5 channels of buffered, party line input-output
-Comprehensive built-in test equipment
-Airborne environment

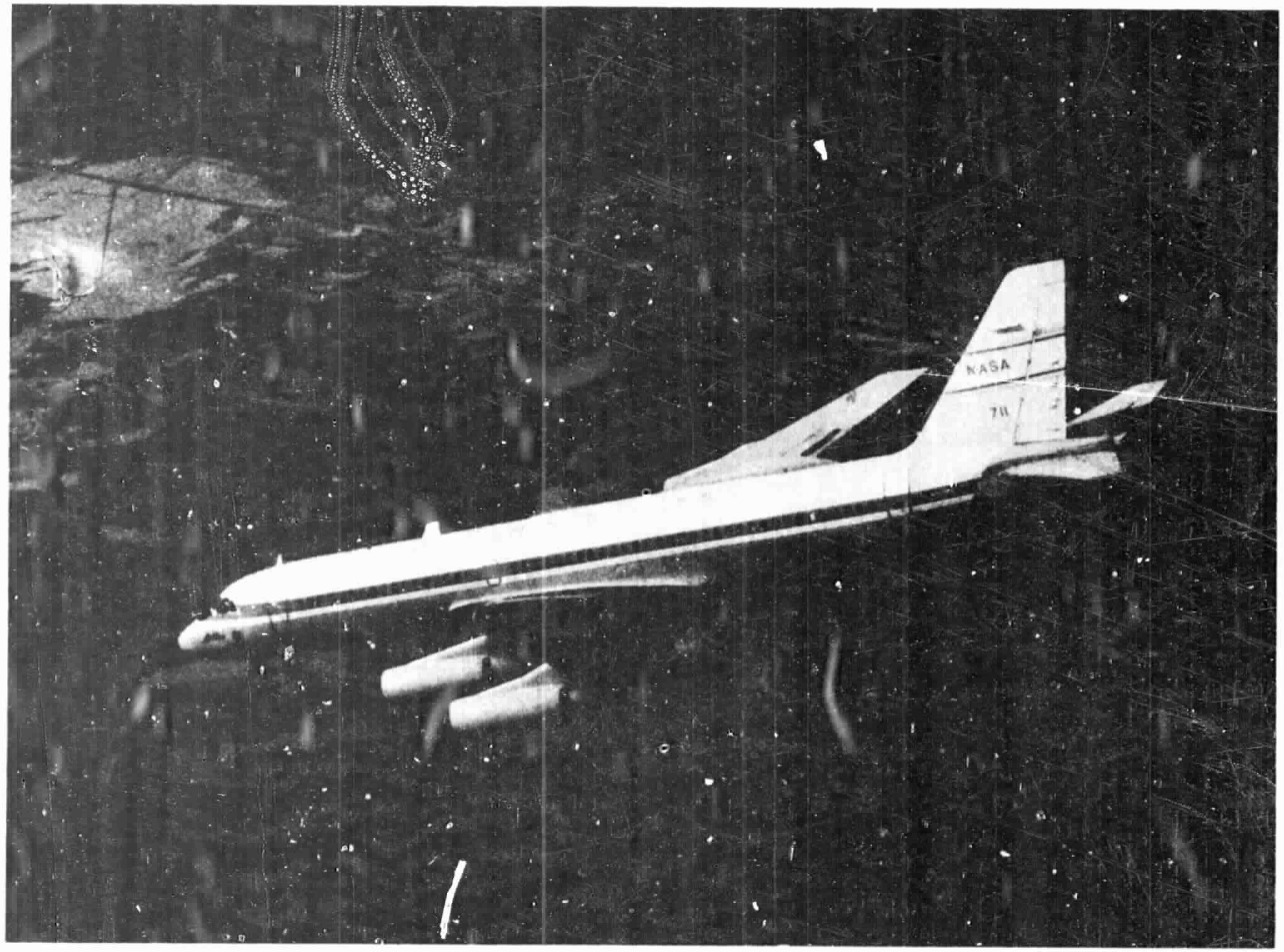


Figure 1.- CV990 during simulated shuttle approach.

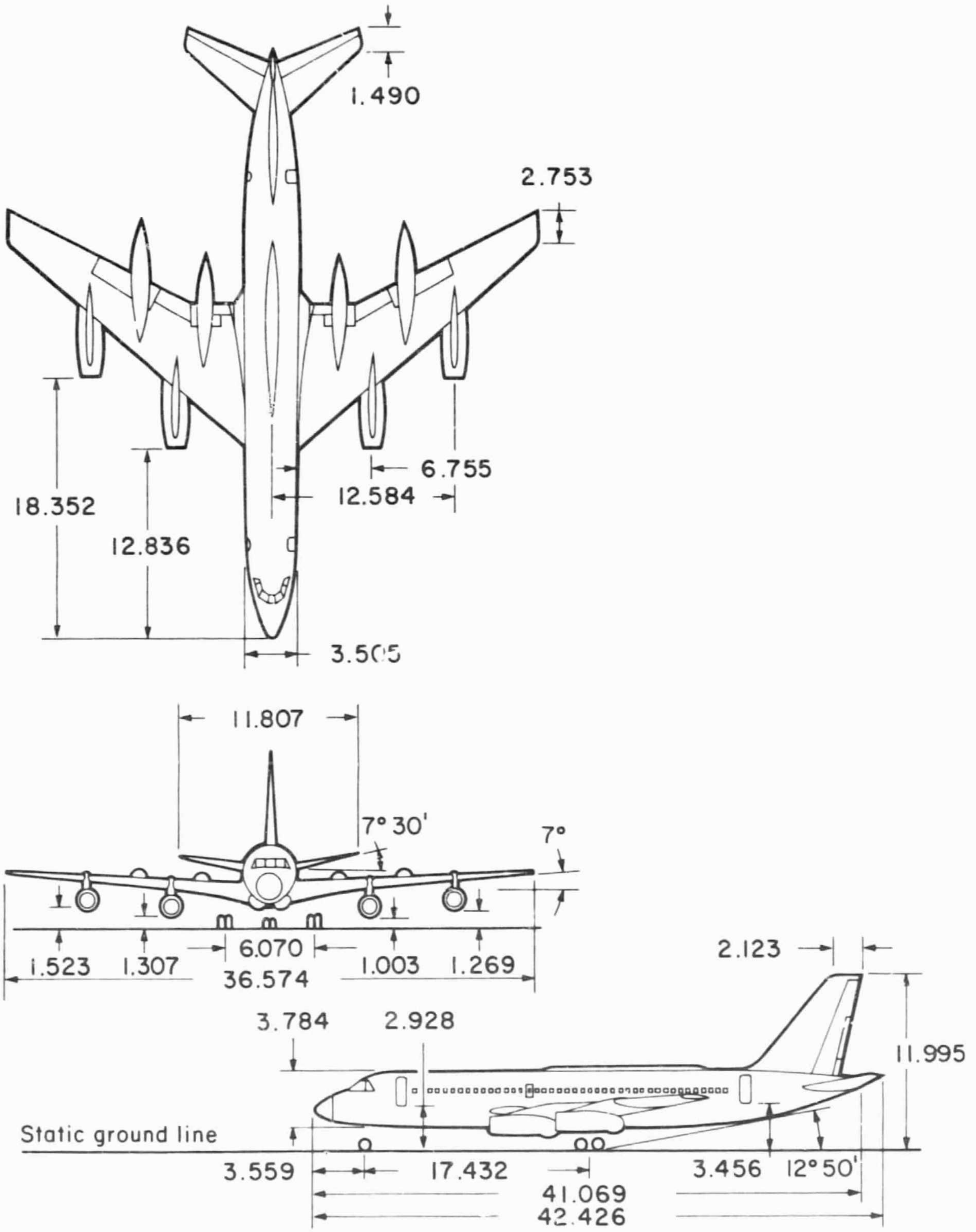
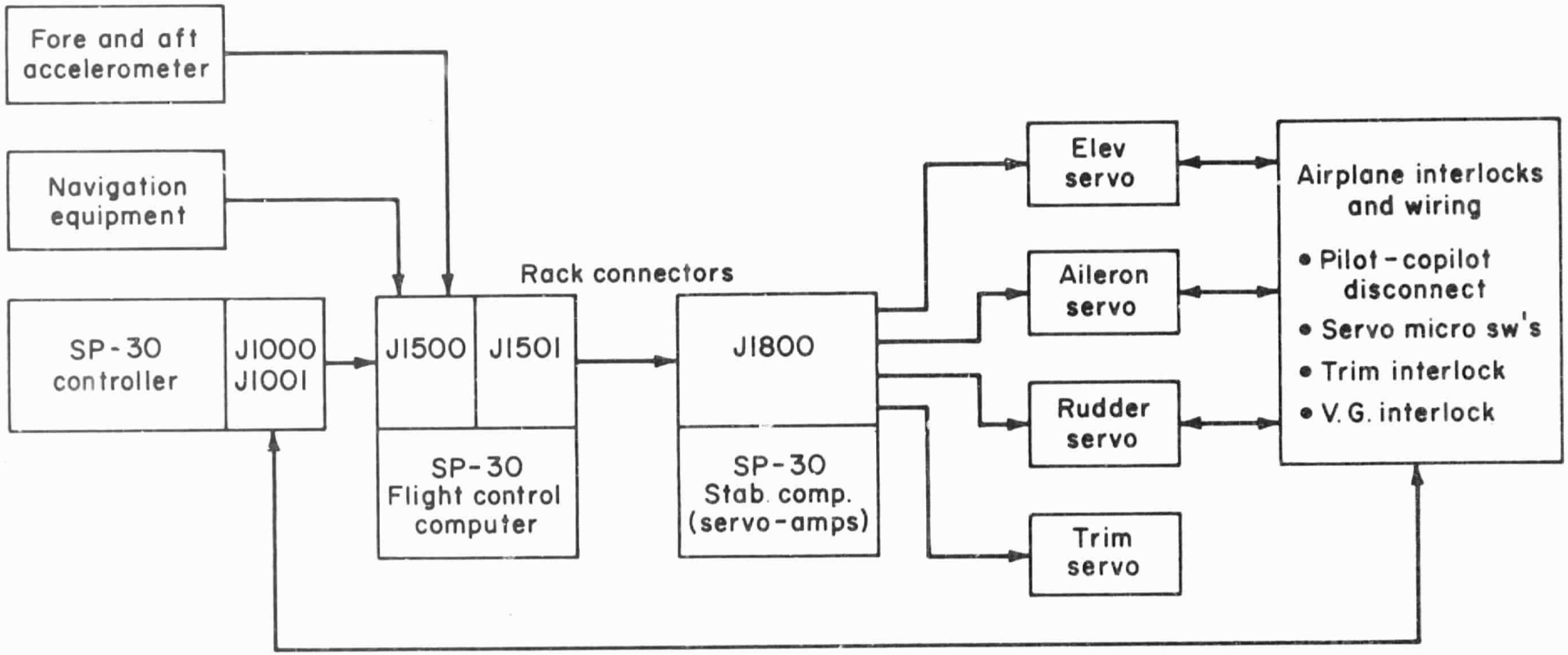
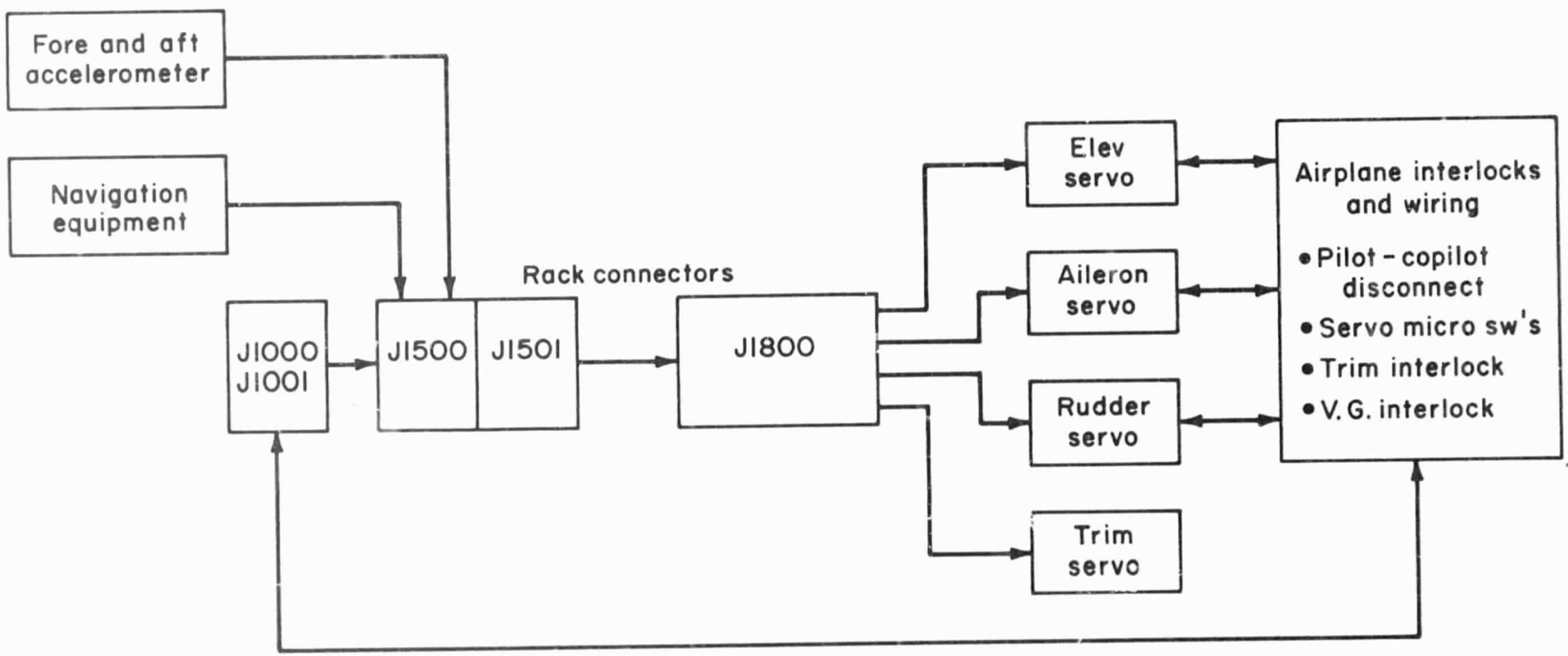


Figure 2.- General view and overall dimensions of the CV990.



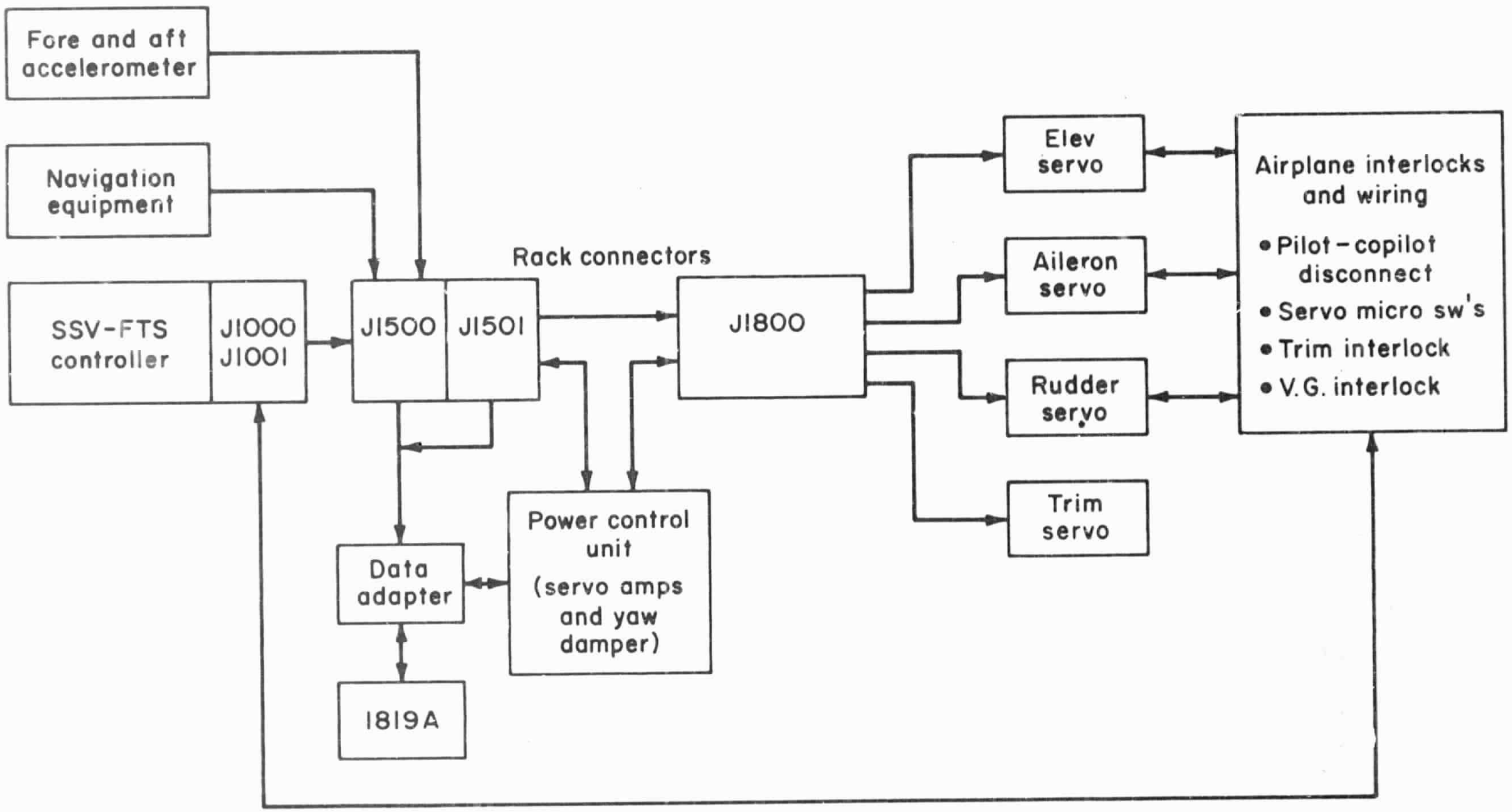
(a) Conventional SP30 autopilot system.

Figure 3.- SS-FTS interface with the aircraft SP30 autopilot system.



Components common to the SP30 and the SS-FTS autopilot system.

Figure 3.- Continued.



(c) The SS-FTS digital avionics system.

Figure 3.- Concluded.

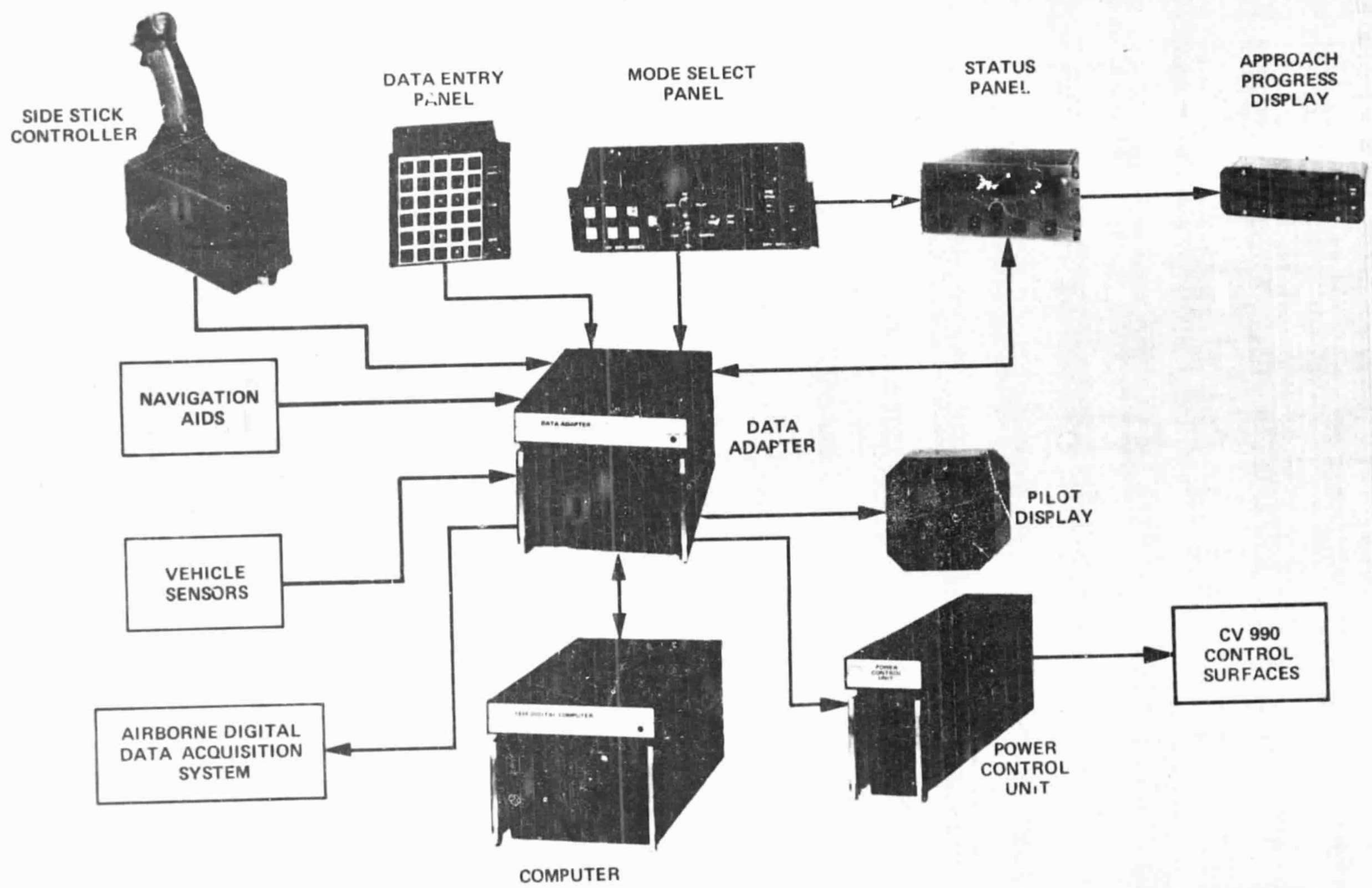
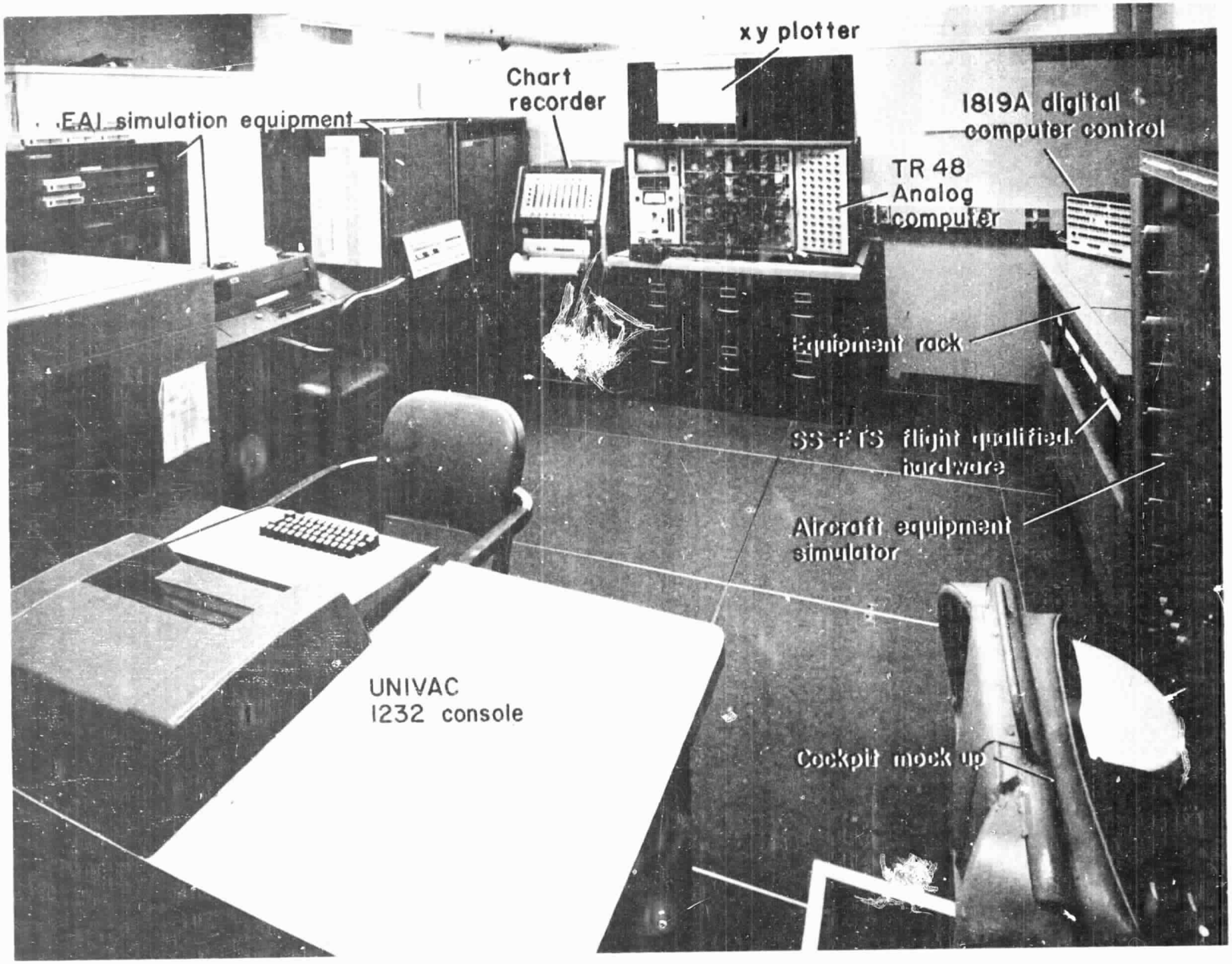
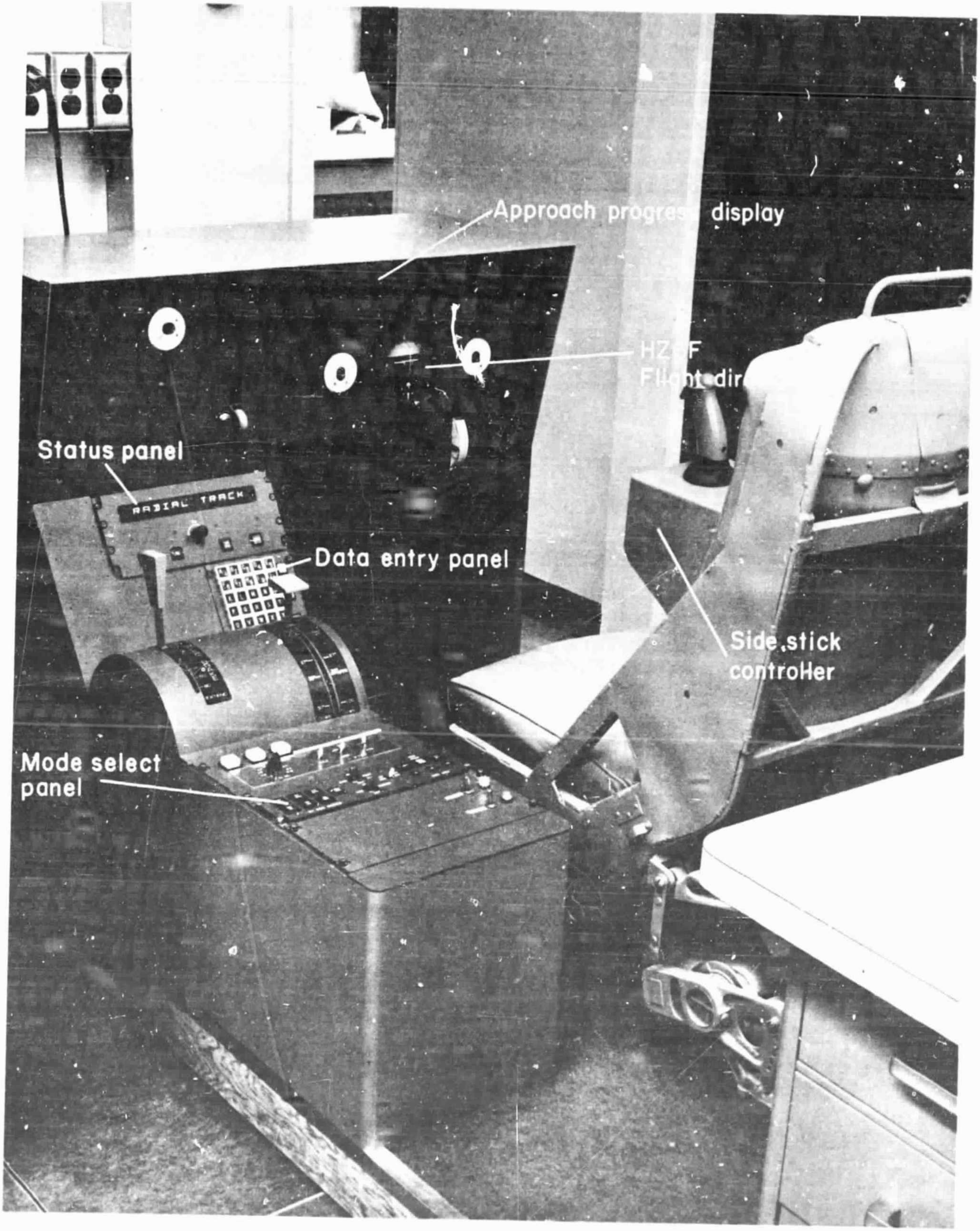


Figure 4.- Simulated shuttle flight test system block diagram.



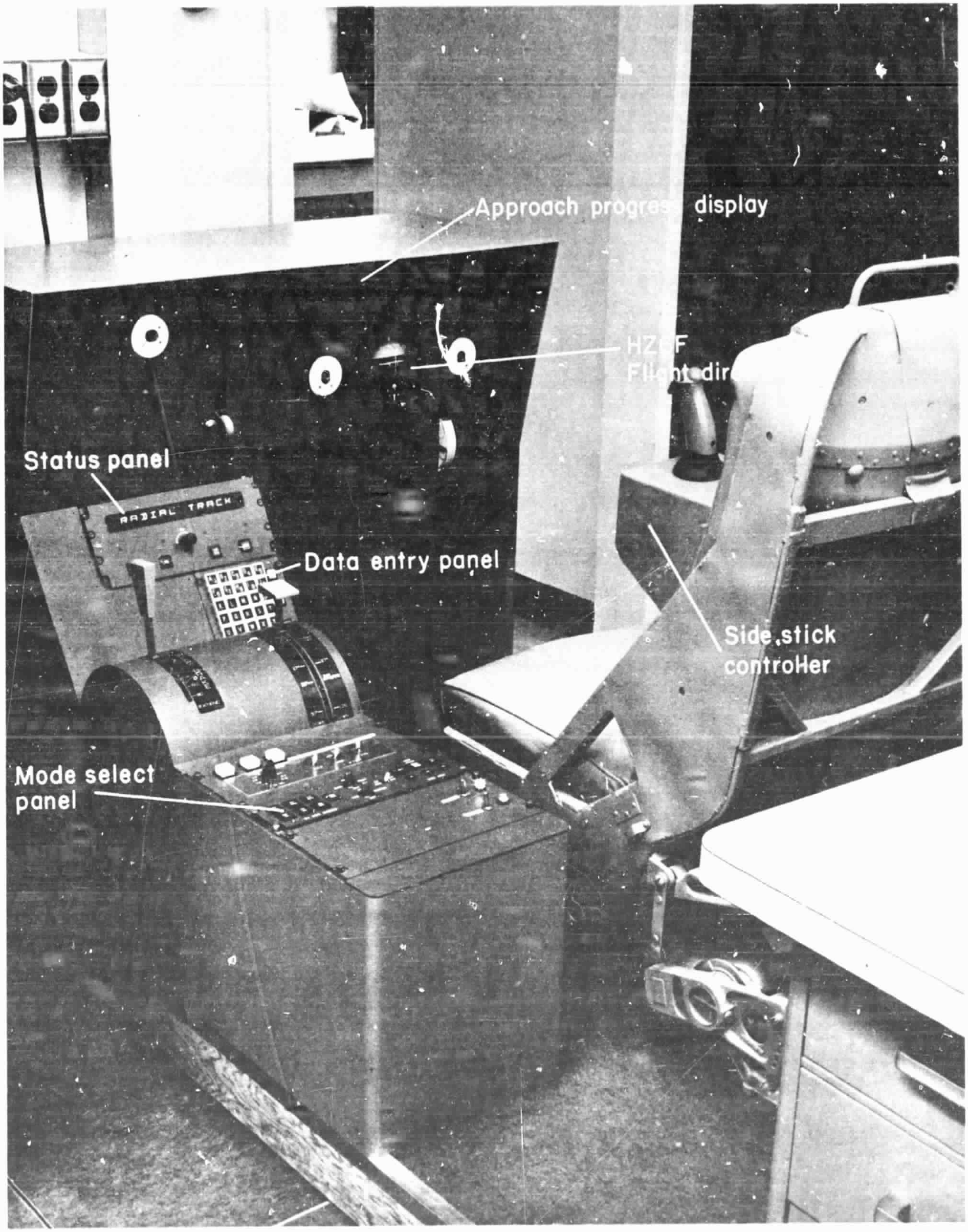
(a) Overall view of the equipment.

Figure 5.- The Validation Facility.



(b) Cockpit simulation.

Figure 5.- Concluded.



(b) Cockpit simulation.

Figure 5.- Concluded.

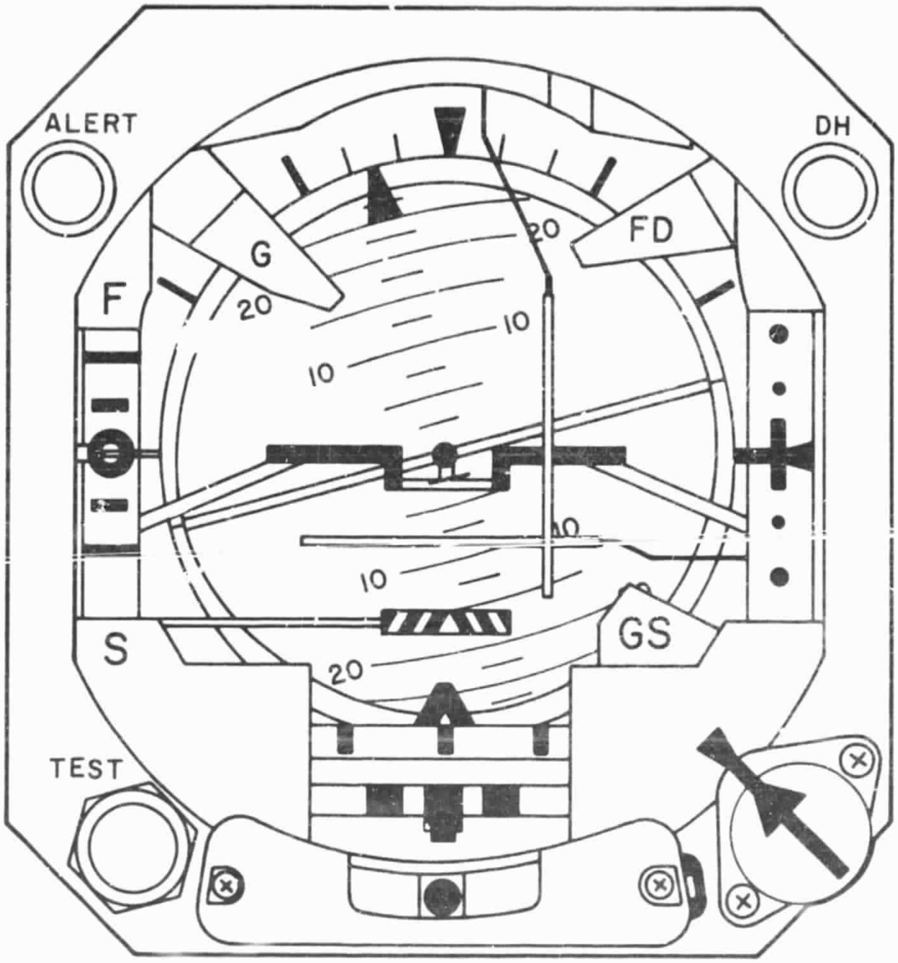


Figure 7.- HZ6F flight director.

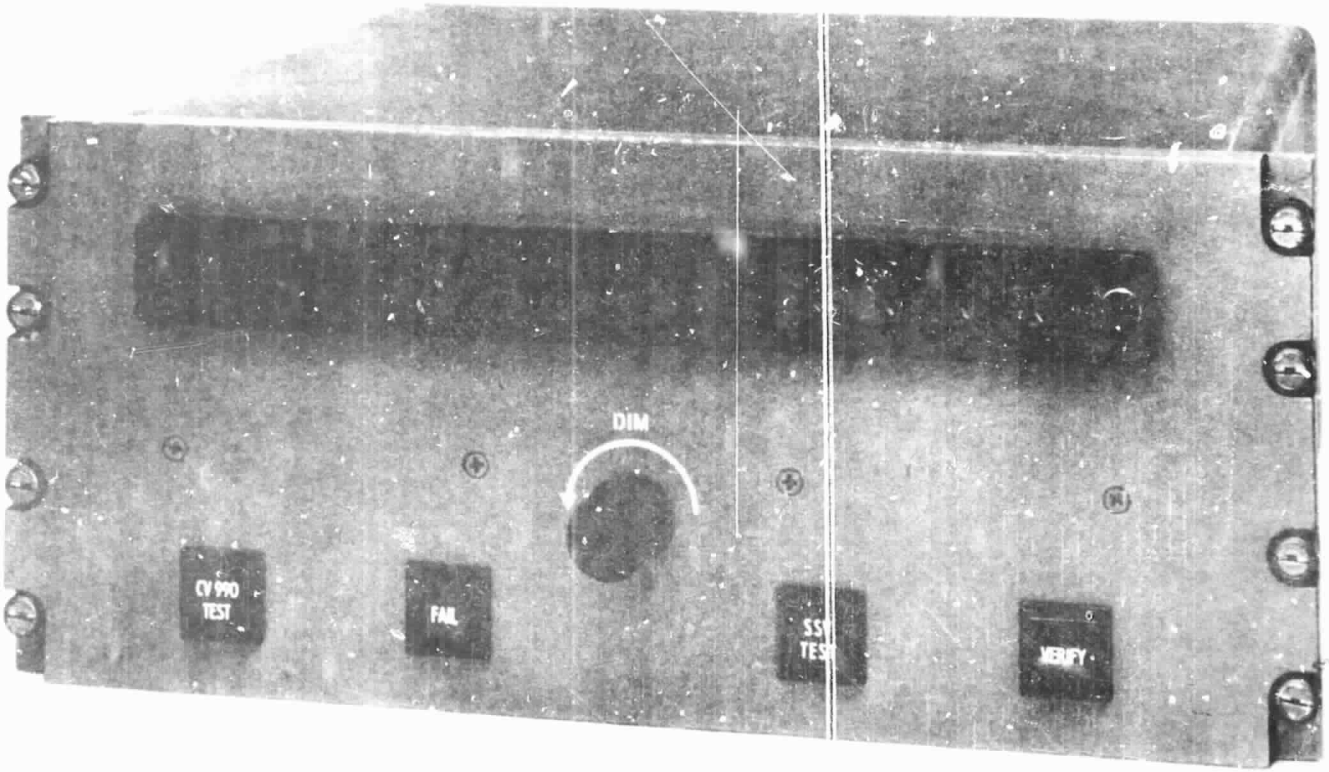


Figure 8.- Status panel.

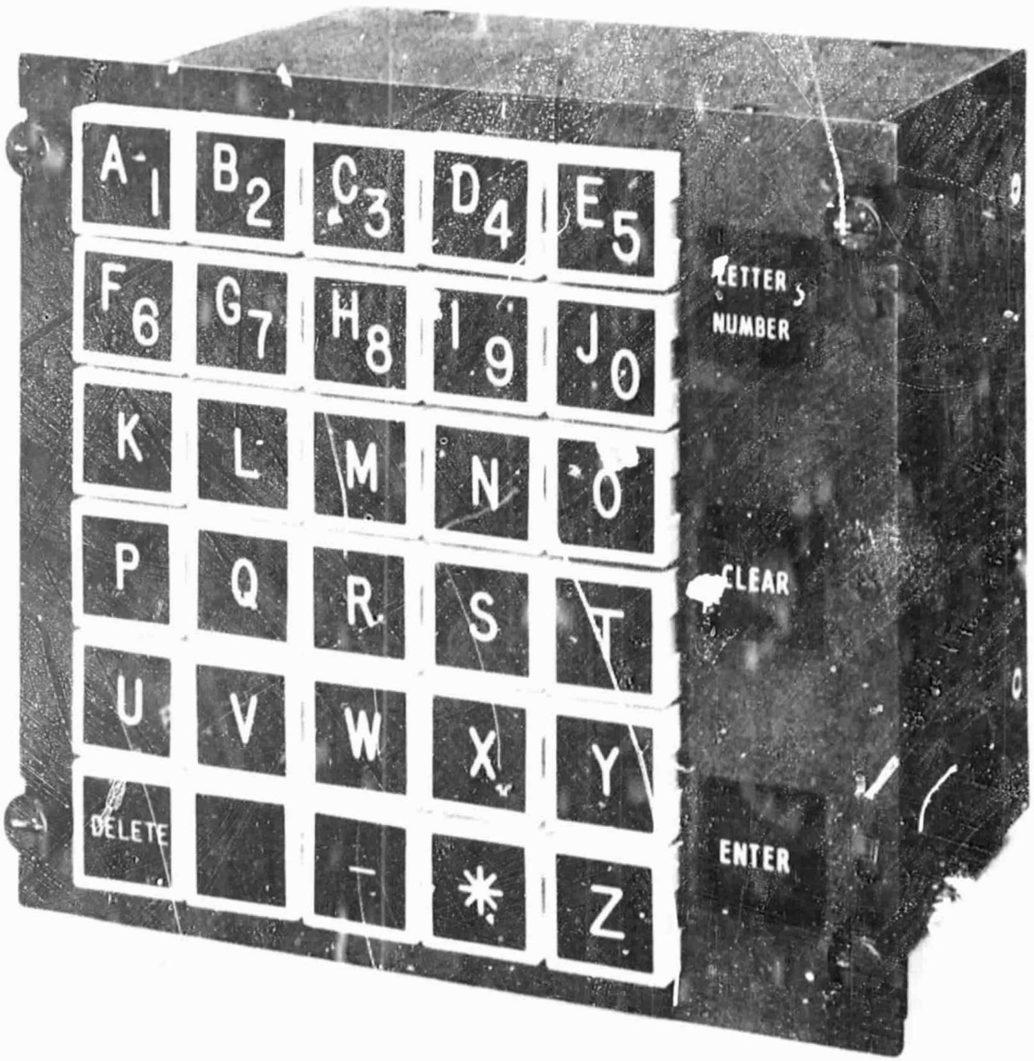


Figure 9.- Data entry panel.

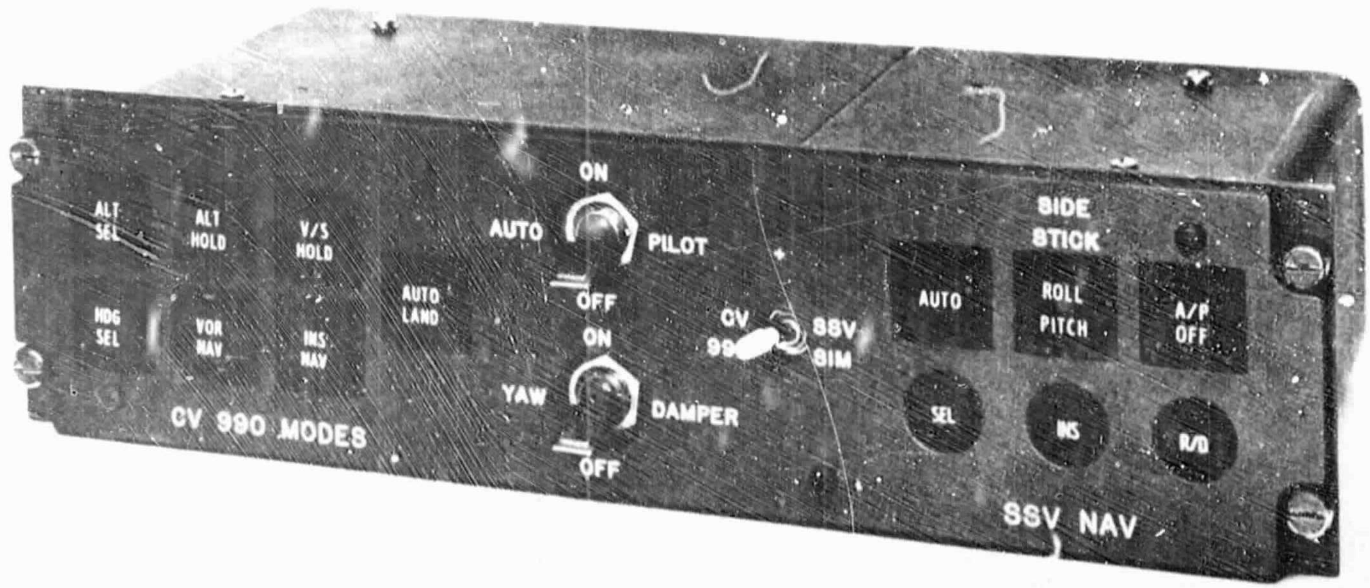


Figure 10.- Mode select panel.

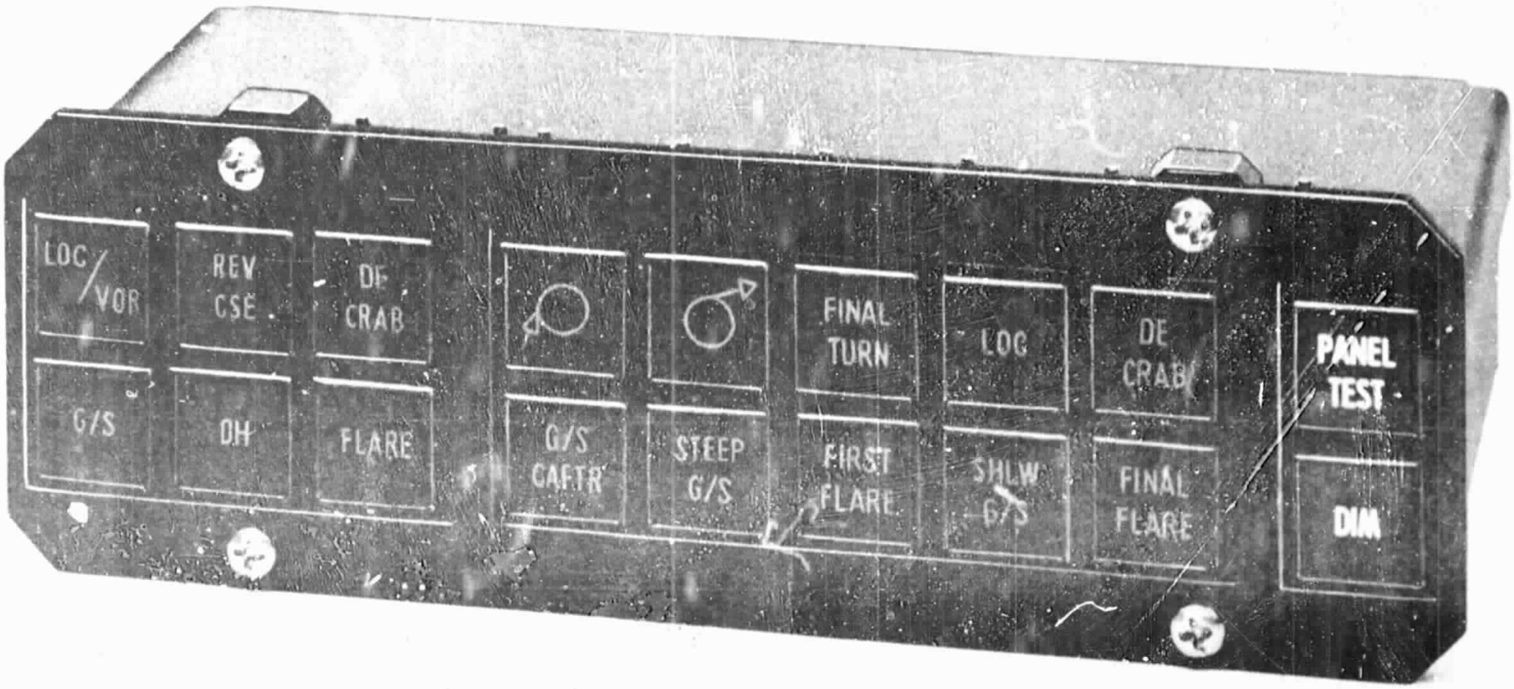


Figure 11.- Approach progress display.

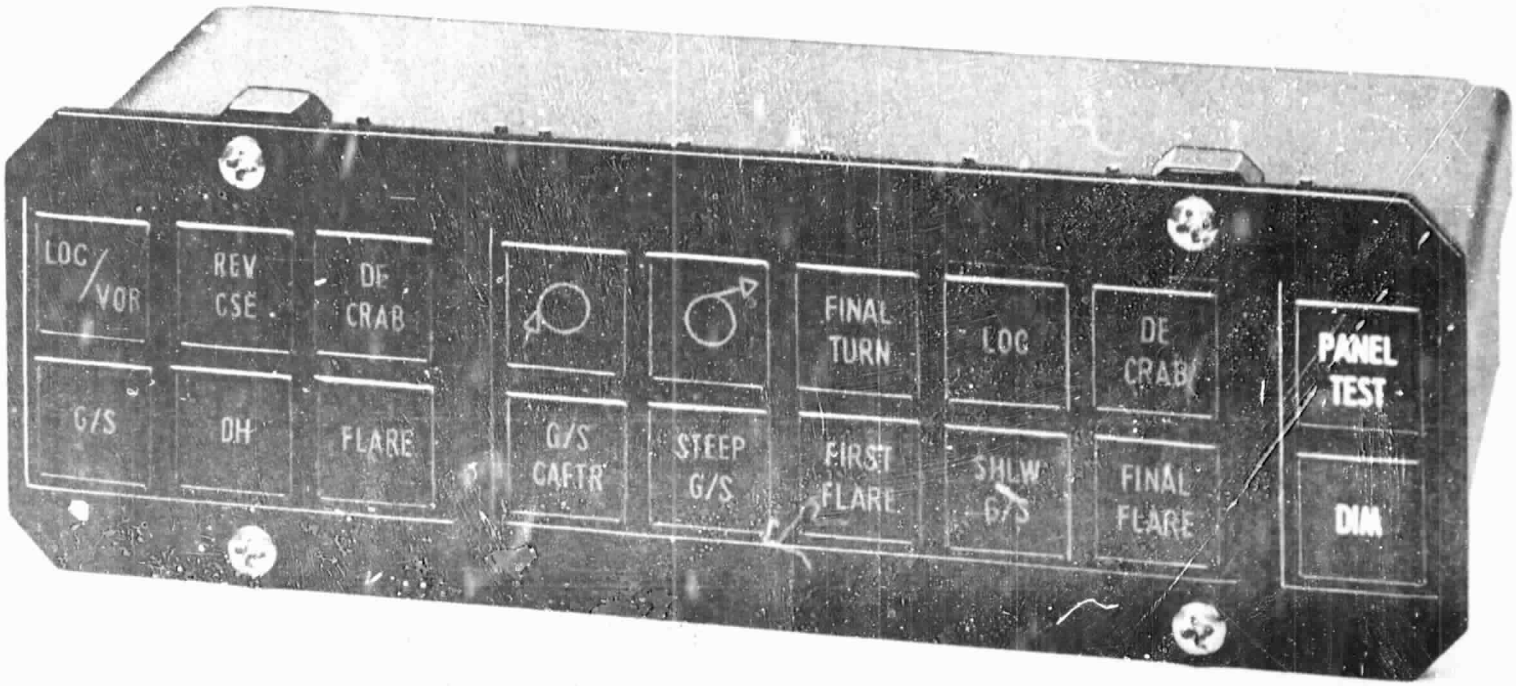


Figure 11.- Approach progress display.

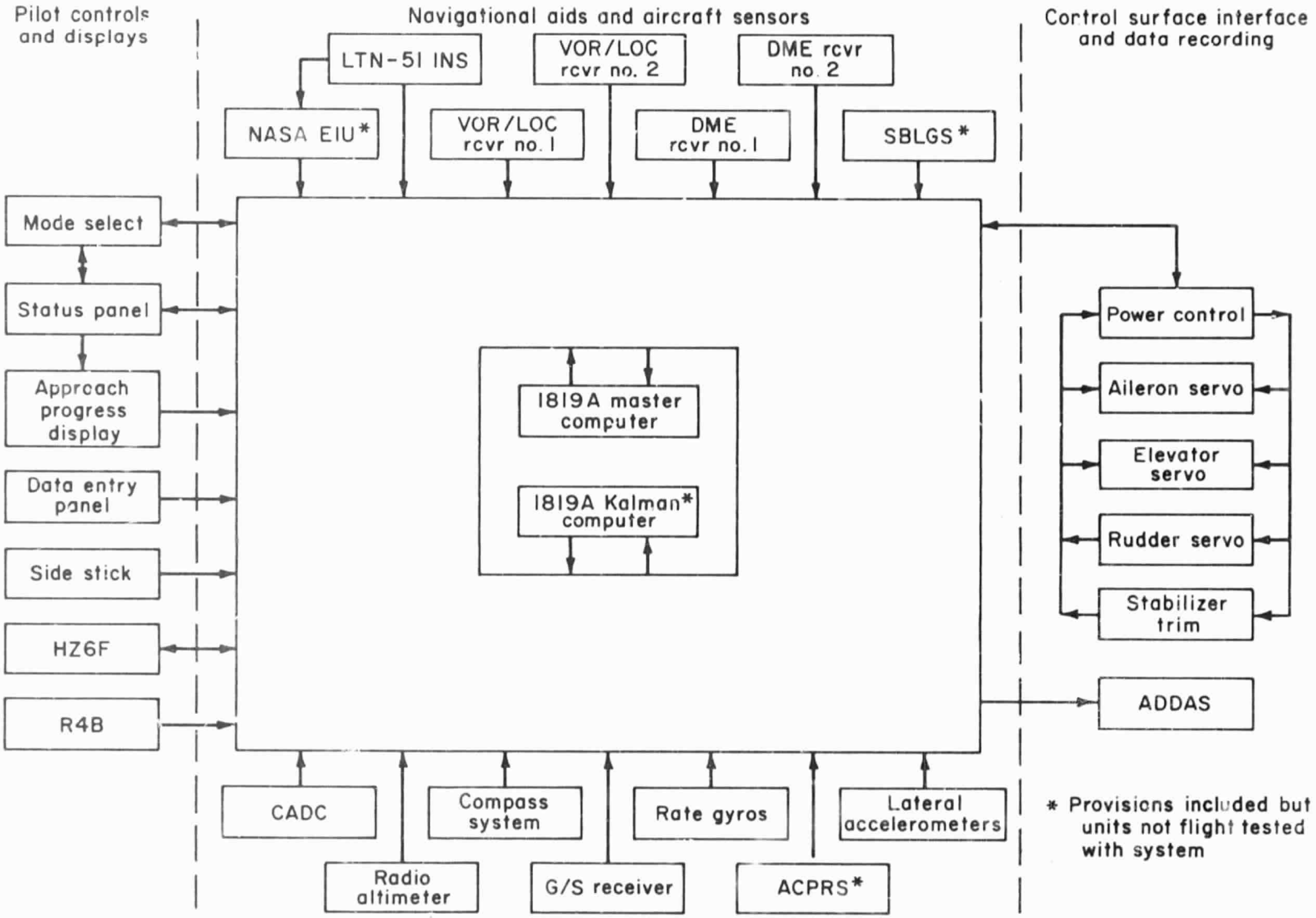


Figure 14.- Data adapter simplified interface block diagram.

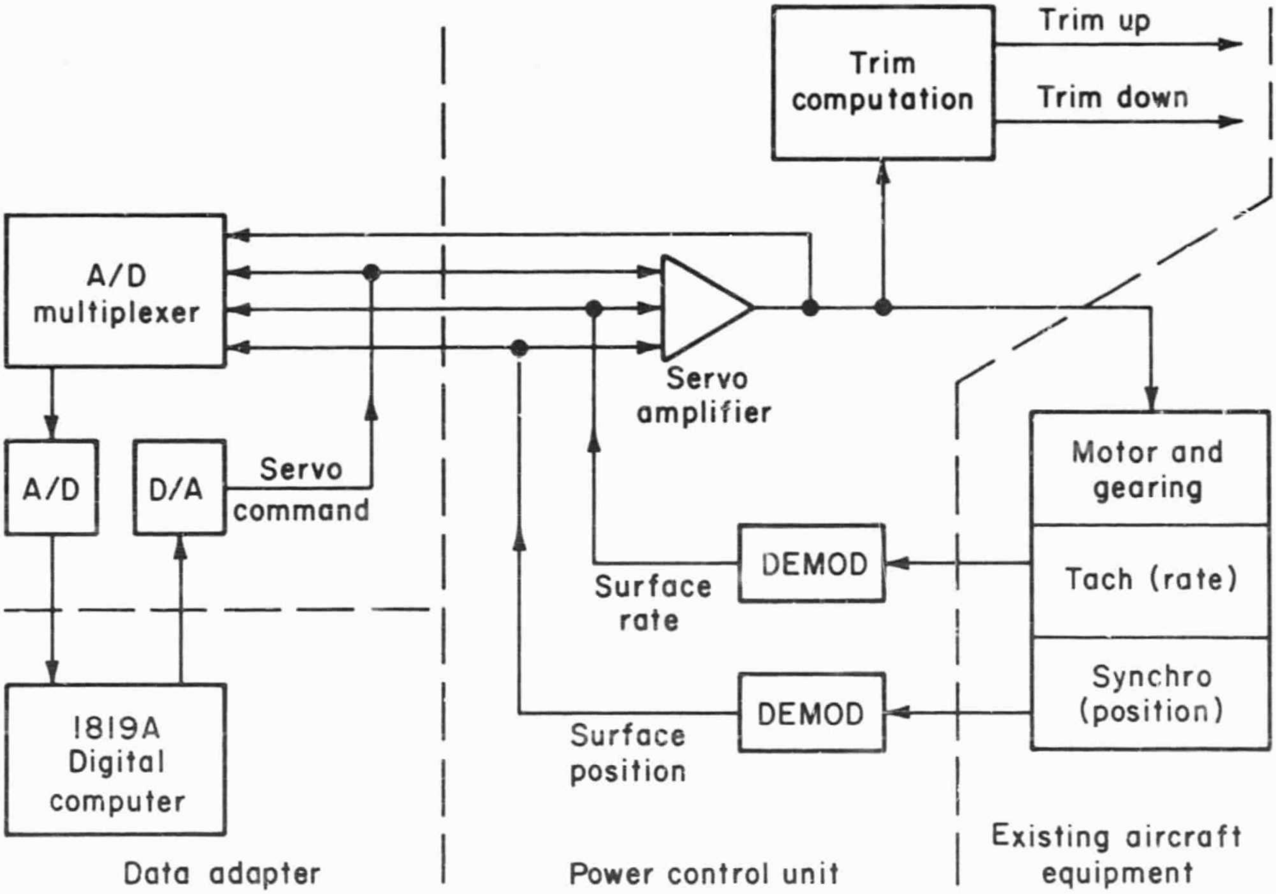


Figure 15.- Servo monitor.

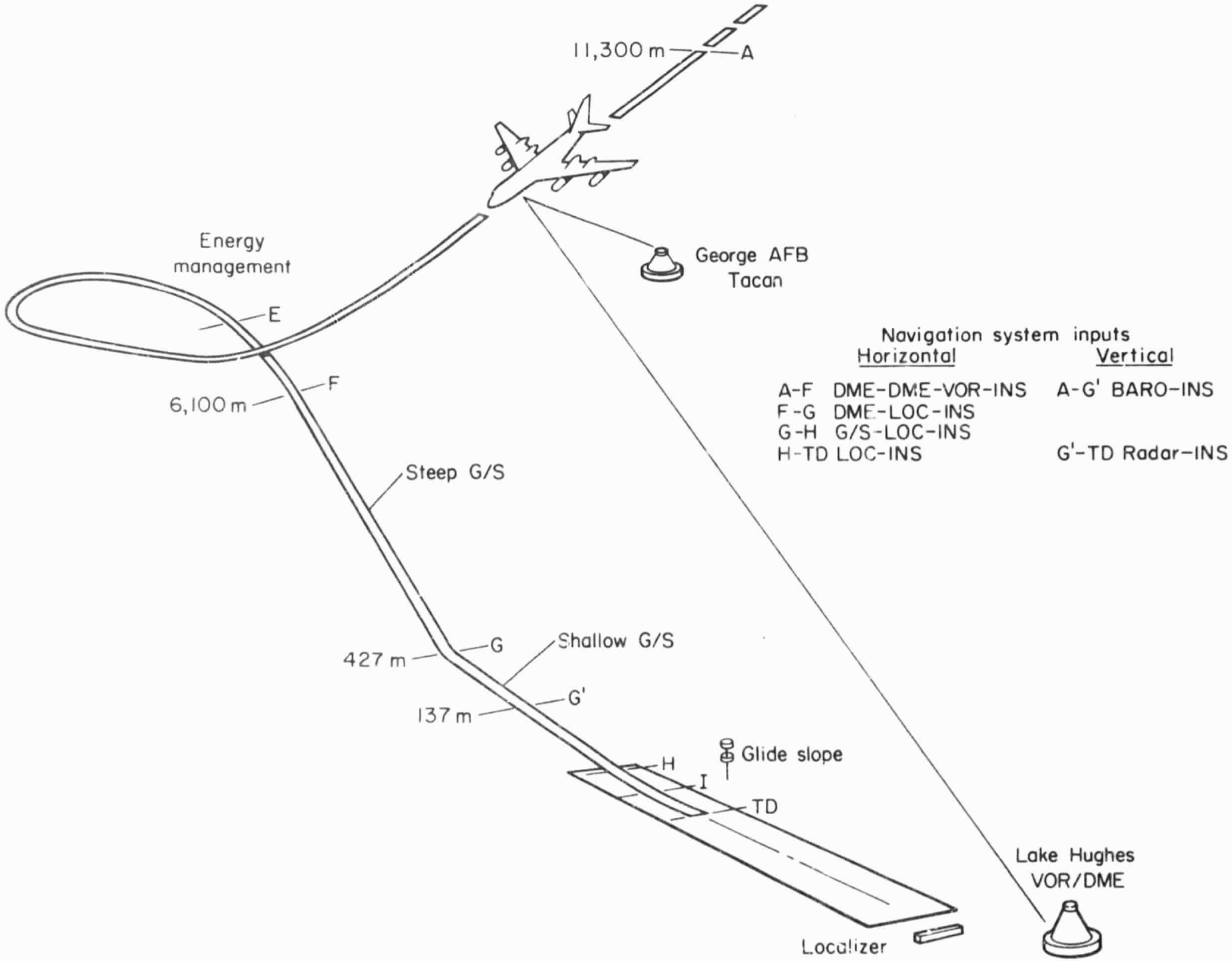


Figure 16.- Navigation concepts on a typical simulated shuttle approach trajectory.

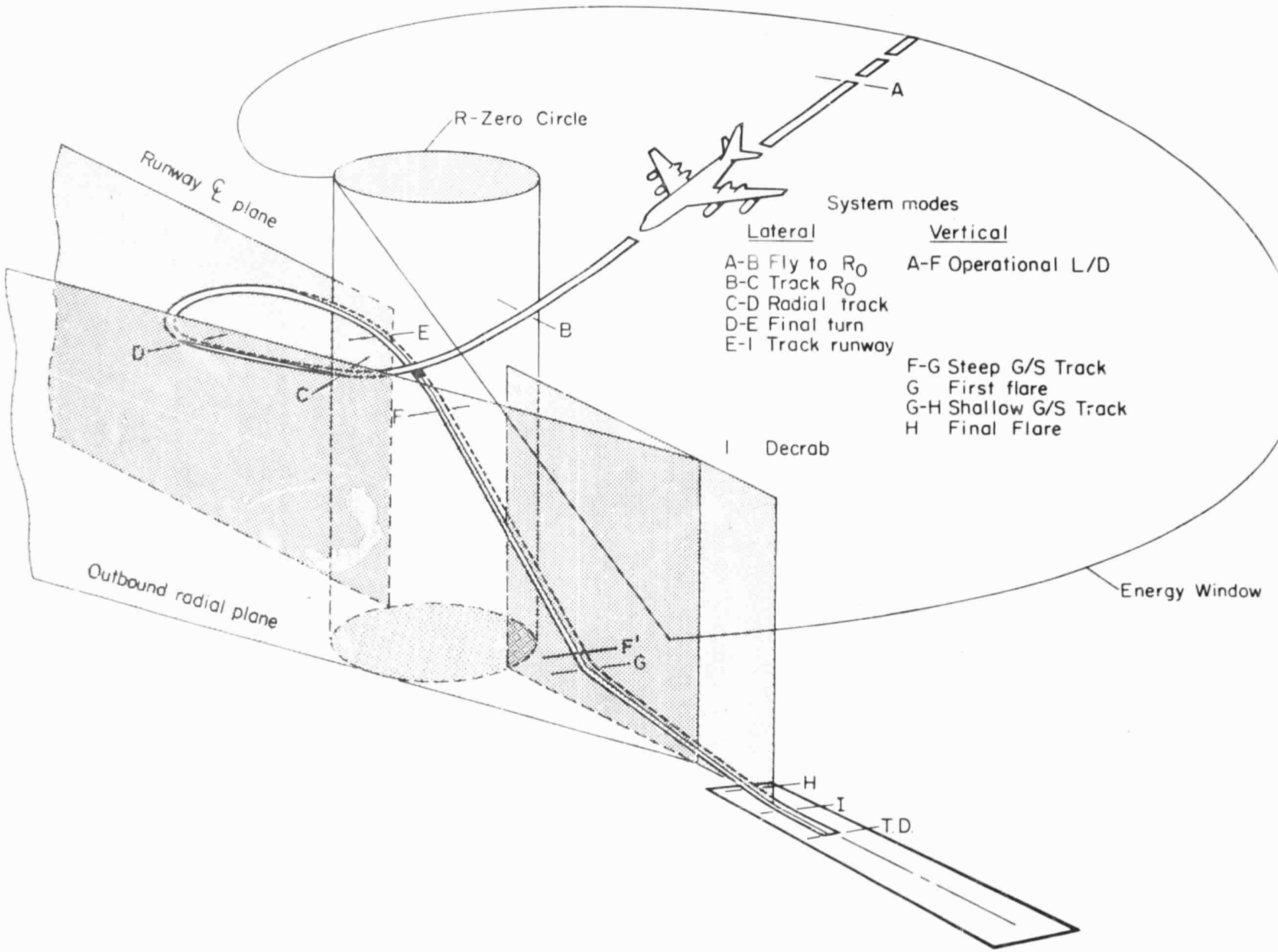


Figure 17.- Guidance concepts on a typical simulated shuttle approach trajectory.

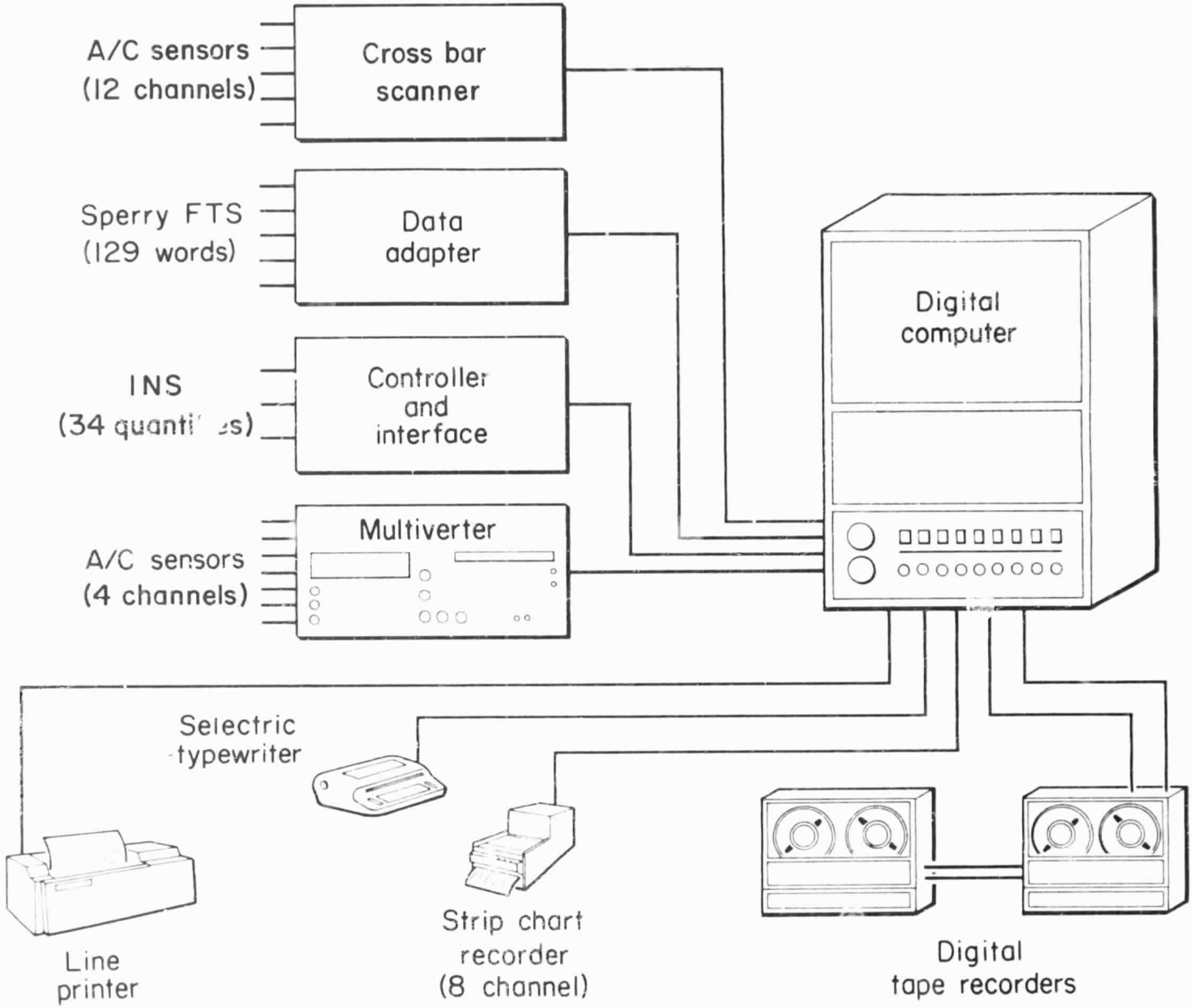


Figure 18.- Airborne digital data acquisition system.